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Development of Electro-Acoustic Soil Decontamination (ESD) Process for In situ Applications

Battelle Columbus Labs., OH

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16. ABSTRACT

The technical feasibility of electro-acoustic soil decontamination process through lab experiments demonstrated the removal/concentration of heavy metals such as cadmium and zinc. Results of the decane contaminated soils were, however, inconclusive. The ESD process is based on the application of a d.c. electric field and acoustic field in the presence of a conventional hydraulic gradient to contaminated soils to enhance the transport of liquid and metal ions through the soils. Electrodes (one or more anodes and a cathode) and an acoustic source were placed in contaminated soils to apply an electric field and an acoustic field to the soil. This process works especially well with clay-type soils having small pores or capillaries, where hydraulic permeability is very low.

The development program included a literature review, soil characterization, design and construction of the laboratory ESD unit, and lab scale experiments with soils contaminated with decane, zinc and cadmium. Evaluation of the experimental results indicated that application of the field sources reduced the heavy metals zinc and cadmium more than 90% in the treated cake. Tests yielded 10-20% decane removal.

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ABSTRACT

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The ESD process is based on the application of a d.c. electric field and acoustic field in the presence of a conventional hydraulic gradient to contaminated soils to enhance the transport of liquid and metal ions through the soils. Electrodes (one or more anodes and a cathode) and an acoustic source were placed in contaminated soils to apply an electric field and an acoustic field to the soil. This process works especially well with clay-type soils having small pores or capillaries, where hydraulic permeability is very low.

The development program included a literature review, soil characterization, design and construction of the laboratory ESD unit, and lab-scale experiments with soils contaminated with decane, zinc, and cadmium. Evaluation of the experimental results clearly indicated that application of the field forces reduced the heavy metals zinc and cadmium more than 90 percent in the treated cake. A maximum of 97.4 percent concentration reduction in cadmium was achieved, and 92.3 percent concentration reduction in zinc was obtained. Tests yielded 10-20 percent decane removal. The results on the decane contaminated soil were inconclusive as a result of the large discrepancy in the decane laboratory analysis.

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DEVELOPMENT OF ELECTRO-ACOUSTIC SOIL DECONTAMINATION (ESD) PROCESS FOR IN SITU APPLICATIONS

by

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FOREWORD

Today's rapidly developing and changing technologies and industrial products and practices frequently carry with them the increased generation of materials that, if improperly dealt with, can threaten both public health and the environment. The U. S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural resources to support and nurture life. These laws direct the EPA to perform research to define our environmental problems, measure the impacts, and search for solutions.

The Risk Reduction Engineering Laboratory is responsible for planning, implementing and managing research, development, and demonstration programs to provide an authoritative, defensible engineering basis in support of the policies, programs and regulations of the EPA with respect to drinking water, wastewater, pesticides, toxic substances, solid and hazardous wastes, and Superfund-related activities. This publication is one of the products of that research and provides a vital communication link between the researcher and the user community.

An area of major concern is the environmental impacts associated with sites contaminated with nonaqueous phase liquids and heavy metals. Because increasing proliferation of these wastes, contamination of the ground and groundwater at a number of locations is causing a serious threat to the environment. Hence, the U. S. Environmental Protection Agency awarded this SITE Program Cooperative Agreement to investigate the technical feasibility of the electro-acoustic soil decontamination concept. This report presents and discusses the development program which included a literature review, soil characterization, design and construction of a laboratory unit , and lab-scale experiments with soils contaminated with organic and inorganic contaminants.

E. Timothy Oppelt, Director
Risk Reduction Engineering Laboratory

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This report was prepared for EPA's Superfund Innovative TEchnology Evaluation (SITE) Program by H. S. Muralidhara, B. F. Jirjis, F. B. Stulen, G. B. Wickramanayake, A. Gill, and R. E. Hinchee of Battelle - Columbus for the U. S. Environmental Protection Agency under Cooperative Agreement NO. CR815324-01-0.

SECTION 1

INTRODUCTION

Many sites in the U.S. are contaminated with nonaqueous phase liquids (NAPL) and heavy metals(1). The U.S. Environmental Protection Agency (U.S. EPA) has estimated that 189,000 underground storage tanks are leaking at retail fuel outlets alone. NAPL contamination in the form of coal tars and petroleum sludges from above-ground tanks is also a significant problem. Following a NAPL spill or release, the liquid typically migrates to the water table where it spreads out and floats, since it is lighter than water. In a typical cleanup, the initial phase recovers the free phase "floating" NAPL. The fraction of spill which is recoverable utilizing conventional technology is very low, and residual contamination following drainage of this recoverable NAPL is very high, often in the range of several percent(2).

Moreover, improper disposal of industrial wastes containing heavy metals has created a serious problem in a number of locations. Because of increasing proliferation of these wastes, contamination of the ground and groundwater at a number of locations is causing a serious threat to the environment.

The current state-of-the-art in remediating these sites is to recover all pumpable separate phase organic liquids and then treat the residuals either in-situ via bioreclamation, soil venting, soil washing or flushing, to pump and treat, or to excavate. The initial recovery of pumpable product depending upon the site, is typically limited to 20-25 percent recovery and in many cases even less. Hence, the U.S. EPA awarded a Phase I Superfund Innovative Technologies Evaluation program cooperative agreement to Battelle Columbus Laboratories to demonstrate the technical feasibility of the ESD concept. This technology will potentially increase the recovery rate and lessen the need for follow-on residual clean up or reduce the cost where some follow-on is required.

This report provides the information related to technical feasibility of Battelle's ESD technology. The report is organized as follows.

Background information related to prior art and theoretical principles on electrokinetics and acoustics is provided in Section 3. Project planning, including QA/QC plan, is given in Section 4. Experimental Investigation, Results and Discussion are provided in Sections 5 and 6, respectively. Technical performance of ESD with other in situ technologies on organic and metal treatment is provided in Section 7. Summary, Conclusions, and Recommendations are provided in Sections 8 and 9, respectively.

The project objective was to establish the feasibility of the in situ ESD for decontaminating hazardous waste sites. The goals of the two-phase developmental effort were to demonstrate the capability of this ESD process to:

- Decontaminate soils containing hazardous organics in situ by the application of d.c. electrical and acoustic fields
- Decontaminate soils containing heavy metals by the application of d.c. electric and acoustic fields.

The program was proposed in two phases: Phase I - Laboratory Investigation and Phase II - Field Demonstration. Phase I objectives were to determine the effects of process parameters on ESD performance and to recommend parameter ranges and a design to be evaluated in Phase II. Phase I consisted of the following tasks:

- Project Planning
- Material Selection/Characterization
- Parametric Investigations
- Assessment of In-Situ Technologies
- Final Report.

This Phase I report includes the background of ESD technology, mechanisms of both the electric and acoustic fields, details of experimental setup, results on decane, zinc, and zinc and cadmium, and summary conclusions of the investigation.

A Phase II small scale field study on heavy metal decontamination is needed to obtain further information related to specification and configuration of the electrodes and acoustic driver in the field.

SECTION 2

BACKGROUND

The ESD process is based on applying d.c. electric and acoustic fields to contaminated soils to obtain increased transport of liquids and metal ions through the soils. Figure 1 illustrates the operating principle of the process. Electrodes (one or more anodes and a cathode) and an acoustic source are placed in a contaminated soil to apply the electric and acoustic fields to the soil. Increased transport of liquids through the soil is obtained by applying the electric and acoustic fields. The process is expected to be most effective for clay-type soils having small pores or capillaries, in which hydraulic permeability is very slight.

The dominant mechanism of the enhanced flow is electroosmosis resulting from the electric field. In-situ electro-osmosis was first successfully applied to soils by L. Casagrande in the 1930s in Germany for dewatering and stabilizing soils(3, 4). Recently, Muralidhara and co-workers at Battelle have discovered that the simultaneous application of an electric field and an acoustic field produces a synergistic effect and results in further enhancement of water transport(5-14). This Battelle's process is termed electro-acoustic dewatering (EAD). Battelle is actively engaged in the development and commercialization of the EAD process for a variety of industrial and wastewater treatment applications.

Based on our extensive research and development experience in the application of electric and acoustic fields to dewatering and proven soil dewatering technology utilizing electroosmosis, Battelle is utilizing the principles of EAD technology to decontaminate soil in-situ. Background information on theories and operating principles is provided in the following sections. Prior related applications are summarized in Table 1.

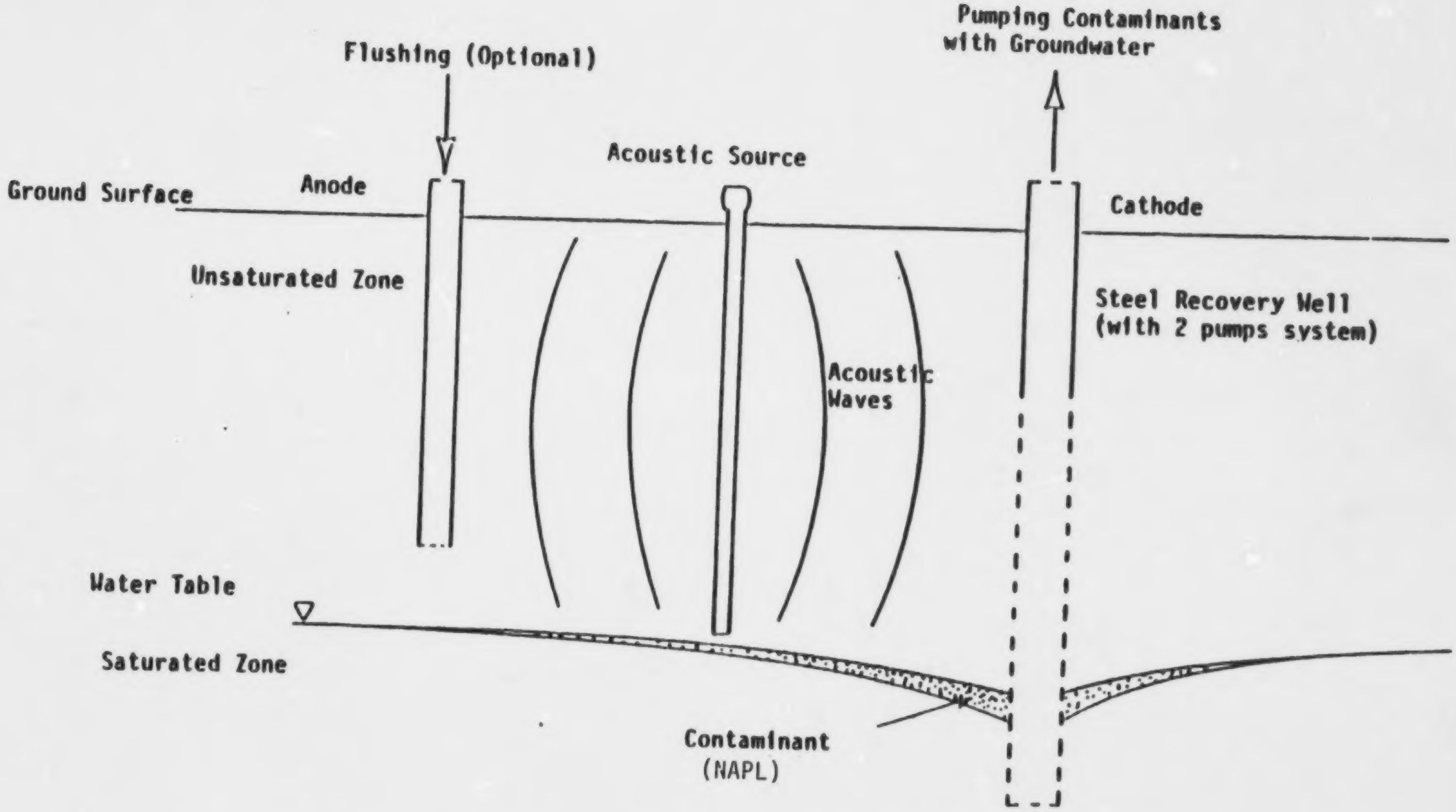

Flushing (Optional)
Pumping Contaminants with Groundwater
Acoustic Source
Ground Surface
Anode
Cathode
Unsaturated Zone
Steel Recovery Well (with 2 pumps system)
Acoustic Waves
Water Table
Saturated Zone
Contaminant (NAPL)

Figure 1. Conceptual Layout of Electro-acoustic Soil Decontamination (Final design may vary based upon laboratory testing).

TABLE 1. APPLICATIONS OF ELECTROOSMOSIS IN SOIL LEACHING, CONSOLIDATION, AND DEWATERING

Application	Investigators	Scale of Operation	Voltage and Current	Results and Comments
Leaching of Cr from soils	Banarjee(22)	Laboratory	0.1 to 1.0 V/cm	• Obtained increased leaching rate with electric field
Leaching of Cr from soils	Horng et al. (23)	Laboratory and field	N/A	• Obtained increased leaching rate with electric field; determined effect of anode materials
Crude oil production	Anbah et al. (24)	Laboratory	N/A	• Obtained increased flow of oil-water mixture through porous media; determined beneficial effect of a small addition of electrolyte to kerosene to obtain increased electroosmotic flow
Soil consolidation	Hardy (21)	Laboratory and field	N/A	• Treated highly plastic clays with liquid limits ranging from 45 to 107 and plasticity indices ranging from 27 to 28 and achieved 300 percent increase in the strength of the clay

TABLE 1. (CONTINUED)

Application	Investigators	Scale of Operation	Voltage and Current	Results and Comments
Leaching of salts and organic acid	Probstein *et al*.(27)	Laboratory	1 - 1.5 V/cm	• Looked at model systems such as Kaolin clay saturated with organic acid cacetic acid. Results suggest that current efficiency increases with increase in concentration which is contrary to predictions.
Soil consolidation	Mitchell *et al*.(28)	Laboratory and theoretical development	0.75 V/cm	• An excellent paper on theoretical aspects of electro-osmosis applied to soil consolidation systems

TABLE 1. (CONTINUED)

Application	Investigators	Scale of Operation	Voltage and Current	Results and Comments
Enhanced oil recovery	Fleureau *et al*.(30)	Laboratory	N/A	• Experiments determined the influence of electrochemical phenomena on interfacial tension and wettability parameters. They observed in-situ formation of the surfactants which was responsible for reducing interfacial tension
Electroreclamation in soils	Lageman(25) (Geokinetics N.L.)	Field	Field Study	• Decontamination of heavy metals especially AS,Cd, CO, Cr, Cu, 4g, Ni, Mn, Mo. About 90 percent removal claimed. Remediation costs ranging from $50 per ton to $400 per ton.

TABLE 1. (CONTINUED)

Application	Investigators	Scale of Operation	Voltage and Current	Results and Comments
Soil dewatering (Salzgitter, Germany)	Casagrande(2,3)	Field	180 V 9.5 A/well	• Electrodes placed 22.5 ft deep and 15 ft apart; flow rate increased by a factor of 150 from 10 gal/day well without electric field to 1500 gal/day/well with electric field; energy usage was 0.38 kwh/gal.
Soil dewatering (Trondheim, Norway)	Casagrande(2,3)	Field	40 V 26 A/well	• Electrodes placed 60 ft deep and 15 ft apart; flow rate increased from 6 300 gal/day/well to 70-3040 gal/day/well; energy usage was 0.30 kwh/gal.
Dewatering of waste suspensions	Kelsh(29)	Lab and Field	N/A	• Applications of electrokinetics to number of waste streams such as slimes, ultrafine coal waste, mine tailings pulp, and paper mill sludges.

TABLE 1. (CONTINUED)

Application	Investigators	Scale of Operation	Voltage and Current	Results and Comments
Electroreclamation of contamianted soils	Hammett(26)	Lab	N/A	• Very informative background work and good discussion on electrokinetic aspects of transport of contaminants in the soil.
Desalting from soils	Anand(32)	Lab and Field	50 V/in.	• An interesting approach to transport salt from soil. It is possible to selectively transport (PO_4), (NO_3) to the root zone.
Electroosmotic dewatering	Lockhart(31)	Lab and Field	N/A	• Applications of electrokinetics to dewatering of minerals, coal and a very good interpretation of mechanisms of electroosmosis during dewatering.

ELECTRO-KINETIC PHENOMENA PRINCIPLES

The application of a d.c. electric field to a soil high in clay content results in the following phenomena:

- Electro-osmosis
- Electro-phoresis
- Current flow
- Ion migration
- Joule's heating
- Ion diffusion.

Each of these has implications for the design and operation of ESD processing schemes, which are discussed in the following sections.

Electro-osmosis

Electro-osmosis(3,15) in porous media, such as clays, is due to an electrical double layer of negative and positive ions formed at the solid-liquid interface. For soil particles, the double layer consists of a fixed layer of negative ions that are firmly held to the solid phase and a diffuse layer of positive ions that are more loosely held. Application of an electric potential on the double layer results in the displacement of the two layers to respective electrodes; i.e., the positively charged layer to the cathode and the negatively charged layer to the anode.

Since the particles in the soils are immobile, the fixed layer of the negative ions is unable to move. However, the diffuse layer containing positive ions can move and drag water along with it to the cathode. This is the basic mechanism of electro-osmotic transport of water through wet soils under the influence of an applied electric potential. Figure 2 shows the electrical double layer and zeta potential.

The rate of flow by electroosmosis through a single capillary is given by the expression(3,15):

$$Q = \frac{ED\, r^2 Z}{4\eta L}$$

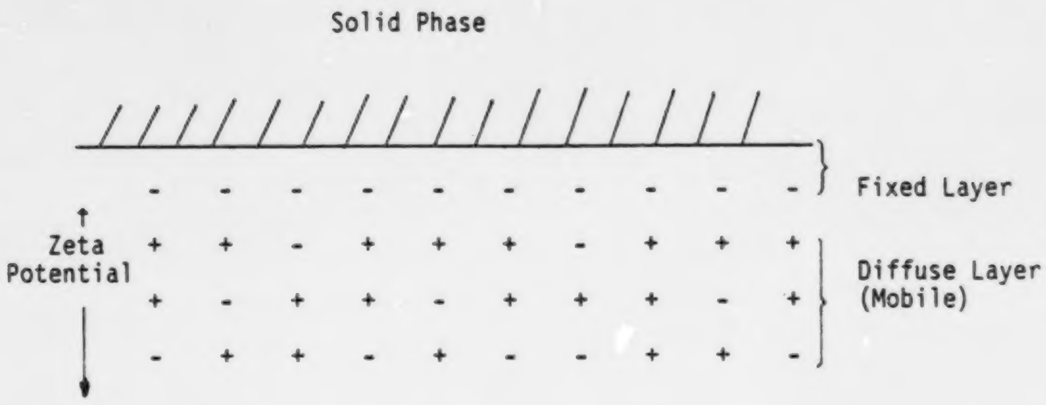

Solid Phase
Fixed Layer
Zeta Potential
Diffuse Layer (Mobile)

Figure 2. Electrical Double Layer and Zeta Potential(14).

where Q = electro-osmotic flow rate, cm^3/sec
E = applied electric potential, volts
L = length of capillary between electrodes, cm
D = dielectric constant of the liquid
g = viscosity of the liquid, (dynes-sec/cm^2)
Z = zeta potential, volts x 10^{-3}
r = radius of capillary, cm

The above expression is valid for soils where pore diameters are large compared with the thickness of the double layer. The electro-osmotic flow velocity (U cm/sec) is obtained by dividing the flow rate, Q, by the cross-sectional area of the capillary (pr^2) as follows:

$$U = \frac{EDZ}{4pgL}$$

The above expression indicates that the electro-osmotic flow velocity is independent of the capillary diameter, a key advantage of electro-osmosis over conventional flow under a pressure gradient. In the absence of an electric field, the flow of water through small pores essentially stops.

An important parameter of electro-osmotic flow is the zeta potential, Z, which is the potential drop across the diffuse part of the electric double layer that controls electro-osmosis. It represents the electro-kinetic charge which exists at the solid-liquid interface of particles in suspension. Typical values of zeta potential reported by Hunter(15) for various types of soils are given in Table 2. The data indicate that electro-osmosis is more efficient in clay-type soils than in sandy soils.

Some noteworthy examples of the prior work on soil leaching, consolidation, and dewatering by electro-osmosis are summarized in Table 1. Numerous patents have been issued in various applications of electric field for enhanced recovery of crude oil(16-24). The examples demonstrate the feasibility and practicality of electro-osmosis in large-scale applications. The reported electrical energy consumption in the range of 0.3 to 0.4 kwh/gal is low and should be acceptable for soil decontamination applications ($0.015/gal to $0.020/gal power cost). The examples of metal leaching, oil recovery, and Casagrande's work in particular on soil dewatering clearly indicate that the application of the electric field has been successful enough to suggest that Battelle's ESD technology would perform adequately at pilot-scale levels and, eventually, full-scale levels.

TABLE 2. ZETA POTENTIAL OF SOILS*

Type of Soil	Zeta Potential (mV)
Lithium vermiculite	-80
Sodium bentonite	-40
Silica sand	-10
Quartz sand	-25
Kaolin clay	-80

* Ref. 15

Current Flow

When a voltage is applied across an electrolyte solution, there is a current flow that is proportional to the electrical conductivity (or inversely proportional to the resistance) of the solution. This is the familiar Ohm's law:

$$I = E/R \tag{1}$$

where I (amps) is the current, E (volts) the applied voltage, and R (ohms) the electrical resistance. The resistance decreases as ionic strength increases and as the temperature increases.

During the ESD process, it is desirable to minimize the current flow for a given zeta potential to reduce power consumption and to minimize the Joule heating; a discussion of current flow phenomenological effects follows.

Ion Migration

When a direct current is passed through an electrolytic solution, the cathode acts as a source of electrons and the anode acts as an electron sink. Positive ions will travel toward the negative electrode (cathode), whereas negative ions will travel toward the positive electrode (anode). The positive ions have a tendency to accept electrons at cathode surface and negative ions electrons at the anode surface. The overall transport of ions in the bulk medium is defined as ionic migration.

Flux of ionic species in the presence of a d.c. electric field is given by:

$J_i = v_iC_iE$, flux of i species moles/sec cm^2
v_i = ionic mobility of i species cm^2/sec/volt
C_i = concentration of i species, moles/cm^3
E = electric field, E/cm

The ionic mobility is the speed at which the ion moves toward the respective electrode in the applied electric field. This speed is determined by the viscosity of solvent, the conductivity of solvent, the strength of the applied field, and the size and the shape of the ion.

Ion Diffusion

Ionic diffusion is another phenomenon that occurs in an electrolysis medium in the presence of a d.c. electric field. The concentration of ions near the electrode is always higher than the bulk concentration. This enrichment of ions near electrode surface promotes flow of ions from a higher to lower concentration.

Ionic flux results from diffusion is given by:

$J_i = D_i \, YC_i$
J_i = flux of i species moles/sec cm^2
D = diffusion coefficient cm^2/sec
C_i = concentration of i species moles/cm^3

Ion transport resulting from convection is rather minimal in in-situ treatment, due to the nature of flow in the soil medium.

Joule's Heating

When a current passes through a solution, the electrical energy is converted to heat according to the equation

$$q = EI$$

where q (cals/sec) is the heating rate, E (volts) is the applied voltage, and I (amps) the electric current through the solution. This heating of the solution is called Joule's heat. The temperature increase of the soil may be approximated as

$$t_{out} - t_{in} = \frac{EI}{FC_p}$$

where F (gm/sec) is the soil flow rate and C_p (cal/mole, °C) is the soil heat capacity. In addition to the Joule's heat, part of the power input is consumed by electrolysis of water. This electrolysis power loss should be subtracted from the total power to obtain a better estimate of the temperature increase.

Electrolysis

The voltage used in ESD greatly exceeds the potential required for electrolysis of water. Therefore, during ESD, electrolysis occurs. Hydrogen is liberated at the cathode and oxygen at the anode. The evolution of these gases would induce a pH change at electrodes resulting from the presence of H+ and OH- ions. OH- combines with Na+ and similar ions present in the cake at the cathode and passes through the filtrate or precipitate at the electrode. This reaction causes the pH of the filtrate to become basic. For the opposite reasons, the cake at the anode becomes acidic.

Generally the movement of the liquid or the particle occurs during electroosmosis or electrophoresis. However, during electrolysis, the movement of ions or complexing of ions occurs. It has been observed that generally the ions' mobility is an order of magnitude larger than electro-osmotic velocity and hence the total energy required to move the ion through the soil column should be much less than electro-osmotic velocity.

According to Lageman(25) of Geokinetics, the following factors play a key role in determining the efficiency of the electrolysis process during heavy metal decontamination of the soil. The factors are:

- Nature of contaminant
- Concentration of heavy metals
- Soil type
- Ionic radius
- Solubility of contaminant as a function of pH
- Ease of release of contaminant from the soil
- pH control around the electrodes.

ACOUSTIC PHENOMENA PRINCIPLES

An acoustic field is one in which the acoustic pressure and particle velocity vary as a function of time and position. These pressure fluctuations form a traveling wave, which propagates from the source throughout the medium. Sinusoidal pressure fluctuations are characterized by their pressure amplitude and frequency. A particle velocity is imparted to the medium by the action of the pressure wave which also varies as a function of time, frequency, and position. Acoustic pressure and particle velocities are related through the acoustic impedance of the medium.

The pressure fluctuations are the result of the transmission of mechanical energy that can perform useful work to bring about desired effects. The type and magnitude of these effects depend on the medium. In acoustic leaching, many of the forces that can contribute to the overall effectiveness include:

- Ortho-kinetic forces, which cause small particles to agglomerate
- Bernoulli's force, which causes larger particles to agglomerate
- Rectified Diffusion, which causes gas bubbles to grow inside capillaries and thereby expel entrapped liquids
- "Rectified" Stokes' force, which causes an apparent viscosity to vary nonlinearly and forces the particle toward the source
- Decreased Apparent Viscosity, which may be due to high strain rates in a thixotropic medium or localized heating which in turn lowers both the viscosity and the driving force to move particles
- Radiation Pressure is a static pressure which is a second-order effect adding to the normal pressure differential.

A precise understanding of the relative significance of each of the listed mechanisms or a given system/medium is unavailable. The contributions to effective acoustic leaching are also dependent on the type of material being treated since all the mechanisms listed depend on the physical/chemical properties of the material under treatment. Therefore, it is difficult to predict performance a priori, and experimental testing is needed to establish baseline performance. A more thorough review is available in the two articles by Ensminger and Muralidhara(14).

To introduce high-energy acoustic signals into the ground, one must address the issues of elastic wave propagation in solids. The earth, for the purposes of in-situ leaching, can be treated as a semi-infinite half space, in which the earth's surface is the boundary of the half-space. It is well known that a source acting normal to and on the surface not only produces acoustic waves (more properly referred to as compression waves in this case) but two additional waves as well. These are shear waves, where particle velocity is perpendicular to the direction of propagation, and surface waves. Surface waves exist at the boundary, extend a given depth into the medium, which is inversely proportional to the wavelength, and produce elliptical particle motions.

Thus, the energy into the source is partitioned into these three types of waves with roughly 10 percent going into compression, 25 percent into shear, and 65 percent into surface waves. Likewise, as the signal propagates from the source, the intensity of the compression and shear waves decrease as the inverse of distance squared because they are propagating in the bulk of the material. Since the surface waves propagate beneath the surface of the material, their intensity decreases as the inverse of the square root of distance. In addition, all three waves will be further reduced by soil attenuation, which generally increases by the square of frequency. Therefore, lower frequency waves will propagate (i.e., penetrate) much further. Buried sources would produce mainly shear and compression waves. The relative amounts depend on the design of the source.

Battelle's experimental work thus far has focused on acoustic (compression) waves. Therefore, it is difficult to state how effective the different wave types would be in leaching, but they may still be effective. Note that the beneficial effects of decreased apparent viscosity may be greatly improved with shear waves.

Another potential application of acoustics is for clearing the skin in the recovery well. As more contaminant particles are driven to the recovery well, the pores and interstitial spaces can become plugged. Beard and Stulen(36) have demonstrated that when acoustic energy is applied to plugged glass frits or limestone specimens, five- to ten-fold increases in flow are observed. This application of acoustics is mentioned here to demonstrate our experience with producing wells. This effect is not part of the ESD technology and is beyond the scope of this proposed work on ESD.

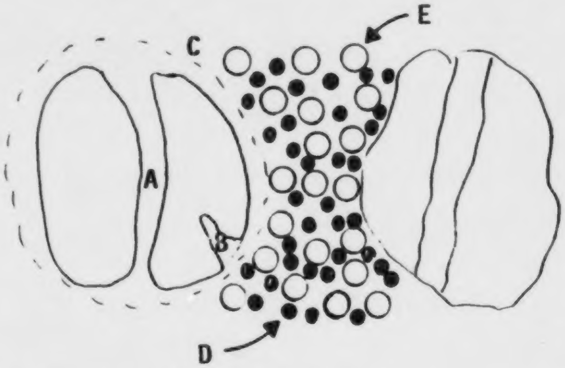
COMBINED ELECTRO-ACOUSTIC SEPARATION PRINCIPLES

Acoustics, when properly applied in conjunction with electro-separation and water flow would enhance dewatering or leaching. The phenomena that augment dewatering when using the combined technique are not fully understood.

However, we have developed some hypotheses about possible mechanisms which can be supported by experimental results.

It is theorized that, in the presence of a continuous liquid phase, the acoustic phenomena (e.g., inertial and cavitation forces) that separate the liquid from the solid into the continuum are facilitated by the electric field and a pressure differential to enhance dewatering by means of one or more of the electro-separation phenomena. There is also evidence of synergistic effects of the combined approach. For example, free radical formation phenomenon should aid electro-separation. In addition, as the cake is densified (by sequestration and electro-osmosis), the liquid continuum would be normally lost, but it is believed that, by channelling on a macroscale, acoustic energy delays the loss of the continuum, making additional dewatering possible. It is the carefully executed combination of techniques to mutually augment the overall solid/liquid separation process that is the essence of Battelle's current EAD process. And because of this combined effect, EAD has been found to be more effective than either electro-separation or acoustically enhanced separation alone. The same effectiveness is expected for ESD.

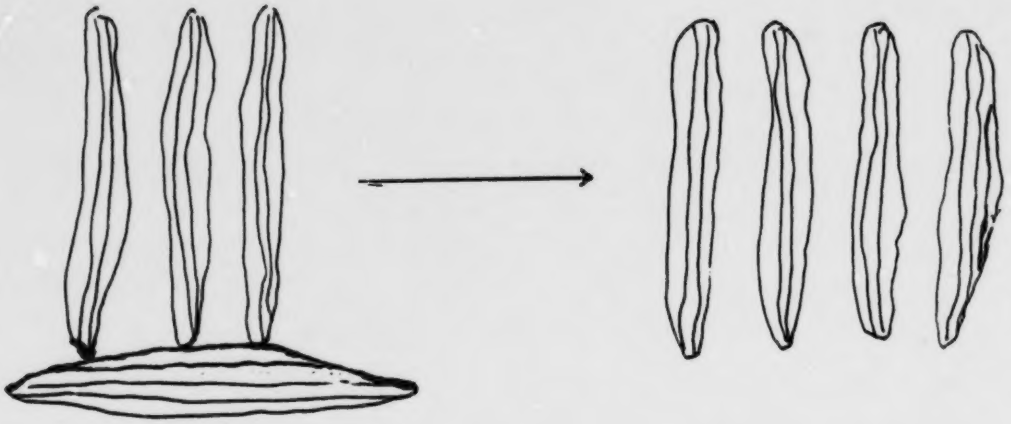
Soil particles are generally colloidal in nature and the structure of the soil particle may be indicated, as shown in Figure 3.



A. Continuous capillary or pore
B. Closed capillary or pore
C. Chemisorbed surface
D. Contaminate between the two particles in a medium
E. Water molecules

Figure 3. Structure of Soil Particle.

Application of electric field will tend to mobilize the liquid present in an open capillary such as A by electro-osmosis. Acoustic field has the ability to pump out the liquid present in closed pores such as B by a mechanism called rectified diffusion (discussed earlier in Section 3.2). Application of acoustic field could also rearrange the particles, creating new channels to assist electro-osmosis, as shown in Figure 4.



Before applying acoustics
(open-ended capillary closed)

After applying acoustics
(open-ended capillaries open)

Figure 4. Rearrangement of Particles from Application of Acoustic Field.

Rearrangement of particles by acoustic field opens up new capillaries, and hence, electro-osmosis becomes more effective. It was postulated that application of electro-acoustics in the presence of hydraulic gradient would basically

- Enhance co-transport of decane with movement of water because of its hydrophobic and light nature
- Transport heavy metals by mere ion migration and electro-osmosis.

SECTION 3

PROJECT PLANNING

This project was conducted under the U.S. EPA's Emerging Technologies Program, which is a part of the Superfund Innovative Technology Evaluation Program. The project sponsored by the Risk Reduction Engineering Laboratory under the above programs required a detail test plan that includes a quality assurance project plan, material selection and characterization, and experimental design. These items were discussed with the project officer as part of the project planning, and the written document experimental design was submitted to U.S. EPA prior to initiation of the study.

QUALITY ASSURANCE PROJECT PLAN

The initial requirement of this program was to develop a Quality Assurance Project Plan (QAPP) that included the following items:

1. Project description and intended use of the data
2. Project organization and responsibilities
3. Personnel qualification
4. Procedures used to assess data quality
5. Quality assurance objectives for critical measurements
6. Experimental procedures
7. Critical test parameters and analytical procedures
8. Data collection, analysis, and reporting
9. Internal quality control checks
10. Performance and system audits
11. Project staffing and percent time on project
12. Schedule
13. Work plan
14. Analytical methods and operating procedures for instruments.

The QAPP was approved by the U.S. EPA before initiating the experimental studies.

MATERIAL SELECTION AND CHARACTERIZATION

Soil Types

Different types of soils contaminated with organics and inorganics at superfund sites can range from highly permeable sandy soils to less- permeable clays. The extent of chemical adsorption to clay is relatively high and mobilization of these compounds from such soils is known to be difficult. Therefore, we proposed to focus most of our efforts on contaminated clay soils to test the applicability of the electric and acoustic fields for decontamination.

The soils for the present study were either clay loam, sandy clay, silty clay, or clay having over 40 percent clay content. Appropriate sources of clay soil were located in Northern Ohio with the help of the U.S. Soil Conservation Service. The soils were classified for their constituents and characterized by particle-size analyses. Soil was also analyzed for organic matter content. All of these analyses were performed by the Ohio Soil Characterization Laboratory, Department of Agronomy, The Ohio State University, Columbus, Ohio. The standard operating procedure for all the analyses is briefly presented in Section 5.

Organic and Inorganic Contaminants

The potential applicability for ESD is expected to range from insoluble organics (e.g., petroleum hydrocarbons and halogenated organic solvents) to inorganics, such as heavy metals (Cr, Cd, Pb) and cyanide. For the screening level studies, we proposed to use a relatively nonvolatile heavy hydrocarbon (decane) and one heavy metal (zinc) as soil contaminants. Decane was selected as the nonaqueous phase liquid because it is a constituent of petroleum products and is used in a number of industries including organic synthesis, jet fuel research, rubber, and paper. It is also used as a solvent. Zinc was selected for our inorganic species because it is one of the heavy metals that is frequently a soil contaminant. Selection of zinc was also based on its low toxicity and relative ease involved in handling, analysis, and disposal. If the heavy metal removal was found to be effective with zinc, additional tests with another metal (e.g., cadmium) would be conducted.

Electrical and Acoustical Properties

Prior to the work in the test unit, ranges of the basic electrical and acoustical properties for a given sample preparation were determined. These parameters include pH, electrical conductivity, acoustical impedance, attenuation, and zeta potentials. These values are expected to be useful in estimating initial parameters for use in the test cell. That is, the intensity of the acoustic source, the placement of the electrodes relative to the acoustic driver, the voltage, and the electrode spacing.

EXPERIMENTAL INVESTIGATION

Preparation of Soils

The clay soil obtained for the present study was mixed with decane to yield a concentration of 8 weight percent (dry basis) or with zinc chloride ($ZnCl_2$) to yield 1 g of Zn per kilogram of soil (0.2 percent dry basis). For additional tests with metals, it was planned that cadmium salts would be mixed with zinc to yield 1 g/kg of Cd and 1 g/kg of Zn. The soil samples with the respective contaminants were thoroughly mixed and four samples from different locations were obtained to determine the uniformity of composition. Decane analysis was performed by a gas chromatographic method, whereas the zinc content was determined by atomic absorption spectroscopy (Section 5).

Bench-Scale Study with a Test Unit

A test unit was constructed as a simple modular design of stacked sections to control the size of the test specimen. The internal dimensions of the test cell were chosen so as to generate acoustic plane waves into the soil sample. A detailed description of this unit is given in Section 5.2.

If the acoustic field is to treat the bulk of the soil in the ultimate application, it is necessary to minimize attenuation. In most homogeneous materials the attenuation increases as the square of frequency. Published data on clays indicate that attenuation at 400 Hz is on the order of 1 to 2 dB per foot, at 1000 Hz is 8 to 9 dB per foot and at 4000 Hz is 20 to 33 dB per foot.(37) Therefore, it is clear that to obtain reasonable penetration, the frequency must be kept under 500 Hz.

At 500 Hz, the wavelength in soil ranges from 3 to 6 in. The internal dimension of the test unit must be less than half the wavelength to propagate plane waves. Therefore, if the test unit is round, the inside diameter should be 3 in. Longer wavelengths (i.e., lower frequencies) can then be accommodated by the same test unit. The advantage of launching plane waves is that the acoustic field will be uniform. That is, every treatment volume will experience the same pressure fluctuations and particle displacements.

The electrodes to generate the electric field were placed in the test cell at a given distance from the acoustic source. These were fabricated as a sandwich with insulating standoffs used to set the interelectrode separation. The electrodes themselves were fairly thin mesh screens to allow the acoustic energy and liquid to pass.

The membranes are thin sheets of rubber on polymer. The purpose of the top sheet was to enable the acoustic waves to pass through the sample without carrying any product from the upper chamber. The purpose of the bottom sheet was to collect the recovered product and enable the acoustic wave to pass on through to the bottom chamber.

The test matrix was designed to evaluate combinations of key parameters to determine recovery rate as a function of the electric and acoustic fields. The test variables and their ranges are as follows:

Applied Voltage or Electrical Power--

The test was conducted for 3 different voltages or electrical power. One voltage was used for duplicate runs. The control experiment was conducted at 0 V.

Acoustic Energy--

The acoustical effects were investigated for 2 frequencies. It was proposed to use one frequency ranging from 200-500 Hz and the other 1000-2000 Hz. A control experiment was conducted without any acoustical energy.

Moisture Content--

During the application of electric field, water in the soil will move from the anode toward the cathode. This will cause the anode layer to become dryer. Since water is the only transport medium for the contaminant, water was introduced at the surface of the anode to maintain the moisture content of the soil and ensure the transport of contaminant. The initial solids percent for the decane contaminated soil was about 53 percent while the initial solids percent for the zinc contaminated soil was about 62 percent.

Treatment Duration--

The test was conducted for 3 or more durations. The leachate volume collected at the effluent port was noted with time.

At the conclusion of each experiment, the soil samples and, if relevant, leachate were analyzed for the respective contaminant. All of the analytical work was performed in Zande Environmental Services, Columbus, Ohio. Some samples were analyzed by U.S. EPA for quality assurance/quality control purposes. The decane and zinc analytical methods are listed in Section 5.

ESD Tests on Decane--

The critical test parameters evaluated in this project are the following:

- Voltage (4 levels)
- Acoustic power (3 levels)
- Acoustic frequency (1 level)
- Voltage and acoustic
- Time (3 levels).

The experimental protocol is described below:

Step 1. Conducted experiments at 4 voltage levels. (0 V/in., 12.5 V/in., 25 V/in., 37.5 V/in.) (4 levels). These voltage levels were chosen based on the conductivity of the suspension. Higher conductivity results in larger voltage, thereby causing excessive electrolysis and internal heating of the suspensions.

Step 2. A second series of experiments was conducted with acoustic power input as a variable at 1 frequency, no electric was used. (0 W, 0.47 W, and 1 W at 400 Hz) (3 levels).

Step 3. Based on the results of Step 1, the best voltage conditions were chosen and, based on Step 2, the best acoustic power setting was chosen, and experiments were conducted at one particular frequency (3 tests).

Step 4. Based on results of Step 1, a series of experiments was conducted with time as a variable. Some of these tests were electric only and some were electric and acoustic.

ESD Tests on Zinc--

The critical test parameters evaluated in this project are the following:

- Electric power (3 levels)
- Acoustic power (3 levels)
- Acoustic frequency (2 levels)
- Time (3 levels).

The experimental protocol is described below:

Step 1. Conducted experiments at 3 power levels (0 W, 0.114 W, and 0.811 W) for 50 hours and no acoustic power.

Step 2. Based on the results of Step 1, the best electrical power condition was chosen and experiments were conducted at three acoustic power levels (0.44 W, 0.88 W and 1.302 W) and one particular frequency (400 Hz).

Step 3. Based on the results from Step 2, the best acoustic power condition was chosen, and an experiment was conducted at the second frequency (850 Hz).

Step 4. Based on the results from Steps 1, 2, and 3, experiments were conducted for 3 times (25 hours, 50 hours and 100 hours).

SECTION 4

EXPERIMENTAL INVESTIGATION

In this section of the report, details of material selection, characterization, experimental setup, experimental procedure, and analytical procedures are discussed. Details are provided below.

MATERIAL SELECTION AND CHARACTERIZATION

Ten 5-gallon containers of 60 percent clay soil were obtained from Paulding, Ohio, with the assistance of the Soil Conservation Service. Table 3 presents the particle-size distribution of the as-received soil. The sand, silt, and clay contents were 10.8 - 11.7, 27.2 - 29.0 and 61.05 - 59.3 percent, respectively. Based on the US Department of Agriculture textural classification, the soil used in the present study falls into the category of clay. The pH and organic carbon contents of the soil are given in Table 4. The soils are acidic and have a pH of about 5.5. The organic carbon content for this clay soil is 1.87 weight percent (dry basis).

Soil Preparation

From each of the ten received containers, 21 lb.s of wet soil (70 percent solid) were dried and mixed together. The dried soil was grounded using an Abbe Fitz mill with an opening of ½ in. screen. The ground soil was used for decane and zinc soil preparation.

Decane Soil Preparation--

Sample of soil prepared by adding 8 weight percent (dry basis) decane in the laboratory. It was found through our laboratory testing that the received soil did not mix well with the decane. The soil appeared to have higher affinity for decane than water. Hence, decane was mixed with the dry soil

TABLE 3. PARTICLE-SIZE DISTRIBUTION OF SAMPLES OF THE SOIL

Particle-Size Distribution (% <2 mm)													
Sand (mm)						Silt (µm)				Clay (µm)			
VCS* 2-1	CS 1-0.5	MS 0.5-0.25	FS 0.25-0.1	VFS 0.1-0.05	TS 2-0.05	CSI 50-20	MSI 20-5	FSI 5-2	TSI 50-2	CC 2-0.2	FC <0.2	TC <2	Text. Class
0.7	1.8	3.0	4.2	1.6	11.2	10.1	5.6	11.8	27.5	39.9	21.6	61.4	Clay
0.8	1.9	2.8	4.0	1.8	11.1	11.7	4.7	11.2	27.5	39.7	21.8	61.5	Clay
0.8	2.0	3.0	4.1	1.7	11.7	4.6	9.1	15.3	29.0	40.2	19.1	59.3	Clay
0.6	1.8	2.8	3.8	1.9	10.8	12.1	4.2	11.0	27.2	39.8	22.4	62.1	Clay

* VCS = Very coarse sand
CS = Coarse sand
MS = Medium sand
FS = Fine sand
VFS = Very find sand
TS = Total sand
CSI = Coarse silt

MSI = Medium silt
FSI = Fine silt
TSI = Total silt
CC = Coarse clay
FC = Fine clay
TC = Total clay

TABLE 4. SOIL CHARACTERISTICS (Four Samples)

Sample	pH		Organic Carbon (Wt. %) Dry Basis
	Water (1:1)	0.01 M (1:2)	
1	5.4	5.1	1.89
2	5.5	5.2	1.88
3	5.5	5.2	1.86
4	5.5	5.2	1.86

first and then with water to provide a homogeneous soil decane mix. The dried ground soil (15 lb.) was mixed with 1.2 lb. decane using a Sigma mixer for 1 hour. Further, the decane-soil mix was mixed with 12.27 lb. of water for another hour. Five batches were prepared following the same procedure. The five prepared batches were mixed and placed in a sealed aluminum pan and stored in a cooler. Five samples were taken from the mixed decane soil and sent to Zande Labs for analysis. The results are shown in Table 5. Although it was intended to prepare 8 percent (weight, dry basis) decane, lab analysis indicated an average of 5.14 weight percent (dry basis) was present in the soil. Further discussion on initial decane concentration is provided in results section.

Zinc Soil Preparation--

The soil sample was inorganically contaminated in the laboratory by adding 0.2 percent of Zn (D.B.) into the soil in the form of $ZnCl_2$. The dried ground soil (15.44 lb.) was mixed in a Sigma mixer for 1 hour with 11.6 lb. of 0.55 percent $ZnCl_2$ solution to provide a soil containing 0.2 percent Zn. The prepared soil was transferred to an aluminum container and stored in a cooler. Five soil-zinc samples were taken from the mixed zinc soil and sent to Zande Laboratory for analysis. The results are shown in Table 6.

Zinc-Cadmium Soil Preparation--

A soil sample (4 Kg) was inorganically contaminated in the laboratory by adding 0.096 percent Zn (D.B.) and 0.1 percent Cd (D.B.) into the soil. Dry soil (15 lb.) was first mixed in a Sigma mixer for 1 hour with 9.0 lb. of $ZnCl_2$ solution to provide a soil containing 0.096 percent Zn. The moisture content of the zinc-prepared soil was 37.5 percent. Then, 8.82 lb. from the above zinc-prepared soil was mixed with 0.86 lb. of 1.05 percent $CdCl_2$ solution to provide a soil containing 0.096 percent Zn, 0.1 percent Cd, and 57 percent solids. The prepared soil was mixed thoroughly and stored in a glass beaker in a cooler. Two soil zinc/cadmium samples were taken from the above prepared soil and sent to Zande and U.S. EPA for zinc and cadmium analysis. The results are shown in Table 7.

TABLE 5. INITIAL PERCENT DECANE CONTAMINATION IN SOIL BEFORE ESD, REPORTED BY ZANDE LAB

Sample	Sample Solids (%)	First Decane Analysis Wet Basis (%)	First Decane Analysis Dry Basis (%)	Corrected Decane Analysis Wet Basis (%)	Corrected Decane Analysis Dry Basis (%)
D1	53.12	3.85	7.25	2.81	5.30
D2	53.48	3.87	7.25	2.83	5.29
D3	53.00	3.36	6.35	2.46	4.64
D4	53.18	3.86	7.25	2.81	5.29
D5	53.01	3.76	7.10	2.75	5.18
Average	53.16	3.74	7.04	2.73	5.14

TABLE 6. INITIAL ZINC CONCENTRATION IN THE SOIL REPORTED BY ZANDE

Sample	Solids (%)	Zn (%), Dry Basis
Z01	57.5	0.1720
Z02	58.0	0.1717
Z03	57.8	0.1795
Z04	58.0	0.1347
Z05	57.9	0.1847
Average	57.9	0.17

TABLE 7. INITIAL ZINC AND CADMIUM CONCENTRATION IN THE ZINC/CADMIUM SOIL

Sample	Zinc Concentration (mg/kg) dry soil		Cadmium Concentration (mg/kg) dry soil	
	Zande	EPA	Zande	EPA
Feed 1	1193	1064	976	866
Feed 2	1052	1064	965	873
	Average = 1093		Average = 920	

TEST UNIT DESIGN AND INSTRUMENTATION

The design of the test unit was developed primarily to accommodate the introduction and characterization of the acoustical energy. The test unit is shown in Figure 5. The intent was to reasonably simulate the field conditions under which the acoustics would be applied. That is, the design was to simulate the earth as much as could be expected in a laboratory apparatus.

Relatively low frequencies (compared to Battelle's EAD work) were chosen because lower frequencies are required to penetrate the earth an appreciable distance. The unit was designed to generate plane-wave acoustics in which points of constant phase form a plane. The direction of propagation is normal to the plane.

This approach reduces the acoustics problem to a one-directional case. In this case, the acoustic field can be characterized with sufficient accuracy with a few point measurements. This is an equivalent situation to the electric field formed by the two parallel-plate electrodes.

The acoustic instrumentation includes an acoustic shaker, a load cell, an accelerometer, and two hydrophones. The acoustic source is an Unholtz-Dickie Model 1 electro-magnetic shaker. This shaker is the source of the acoustic excitation. It transmits a maximum force of 50 lb. and operates between 10 Hz and 10,000 Hz. A Sensotec 31/1432-08 load cell and a PCB-321A02 accelerometer mounted on the acoustic piston assembly were used to measure the force and acceleration levels. These levels were used to calculate the mechanical power input to the system. Two B&K 8103 hydrophones were used to measure the dynamic pressure above and below the test cell. Basically, hydrophone signals indicate the extent of attenuation.

Acoustic data were acquired during testing with the four channel analyzer. This was under computer control (computer not shown in Figure 6) to automate acoustic data collection and storage. Two plots of typical acoustic records that were acquired and stored are shown in Figures 7 and 8. The data in Figure 7 are typical since the signed traces from the load cell, accelerometer and two hydrophones appear as single-size waves at the drive frequency. However, in Figure 8, the load cell and accelerometer signals have significant harmonic content, indicating some nonlinear interaction between

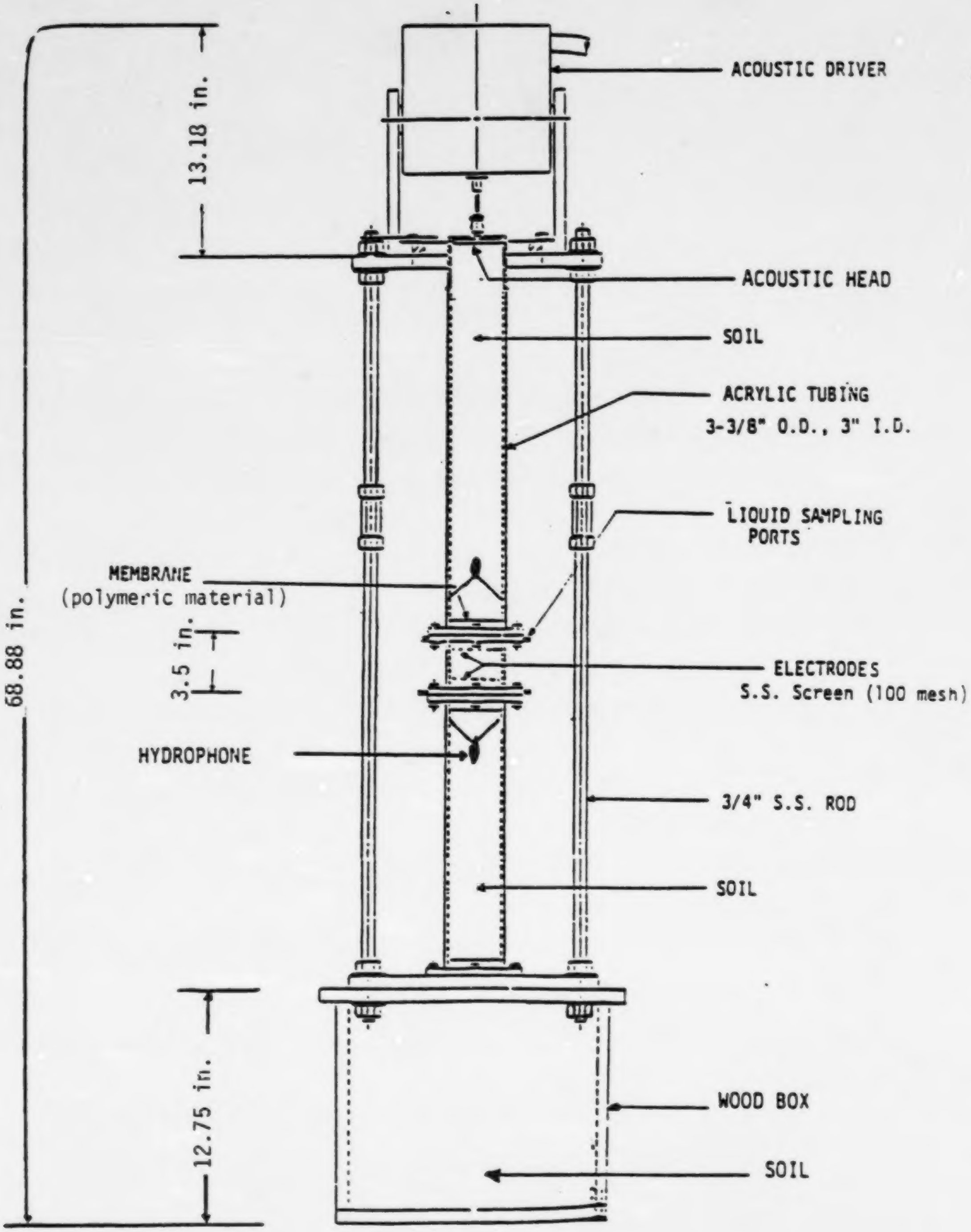

ACOUSTIC DRIVER
13.18 in.
ACOUSTIC HEAD
SOIL
ACRYLIC TUBING
3-3/8" O.D., 3" I.D.
LIQUID SAMPLING PORTS
MEMBRANE
(polymeric material)
68.88 in.
3.5 in.
ELECTRODES
S.S. Screen (100 mesh)
HYDROPHONE
3/4" S.S. ROD
SOIL
12.75 in.
WOOD BOX
SOIL

Figure 5. Schematic of Laboratory Test Unit.

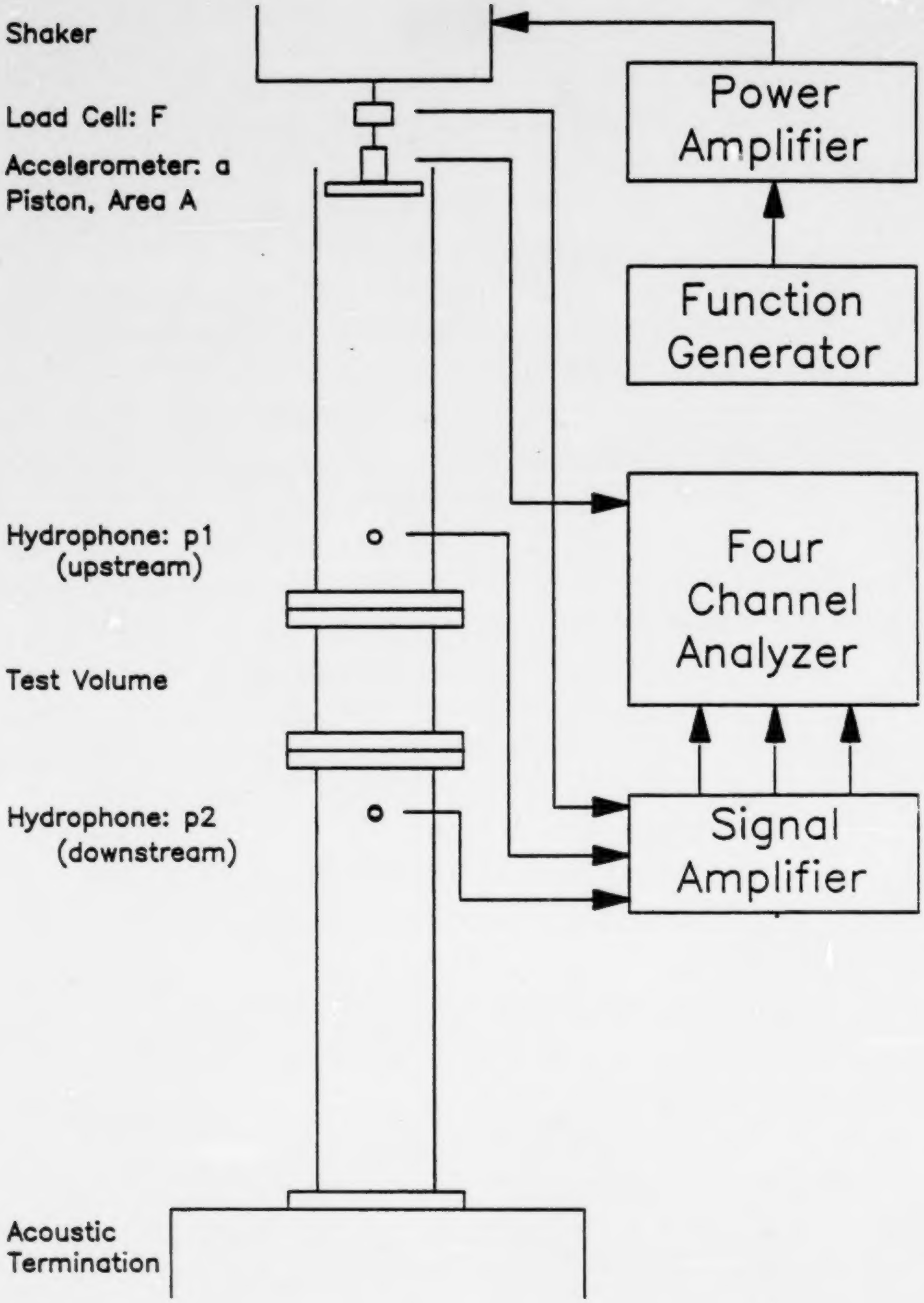

Shaker
Load Cell: F
Accelerometer: a
Piston, Area A
Power Amplifier
Function Generator
Four Channel Analyzer
Hydrophone: p1 (upstream)
Test Volume
Hydrophone: p2 (downstream)
Signal Amplifier
Acoustic Termination

Figure 6. Test Unit and Acoustic Instrumentation.

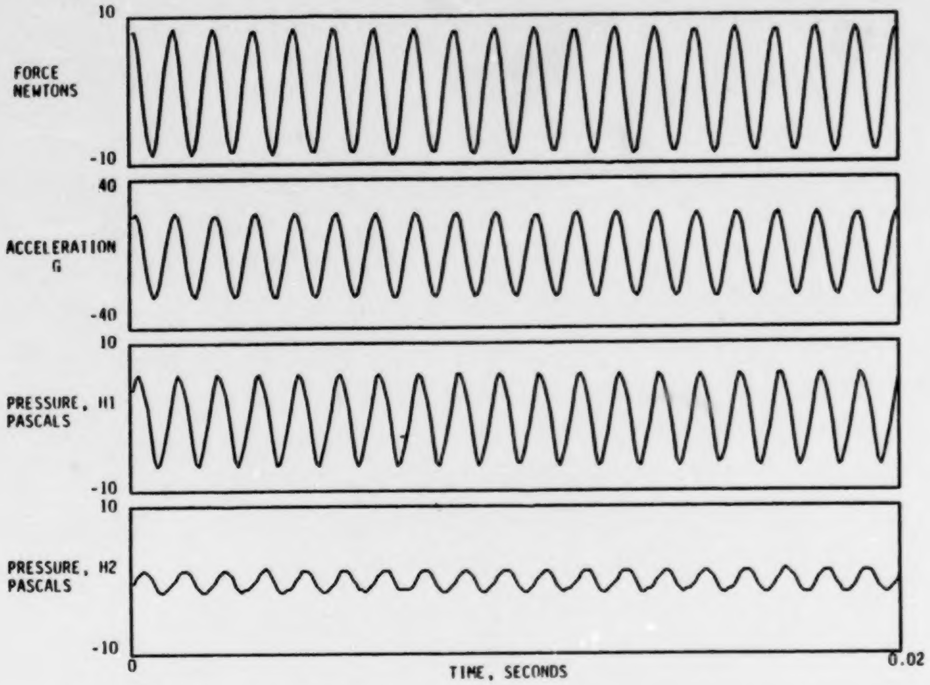


Figure 7. Typical Acoustic Signals Acquired During Testing.

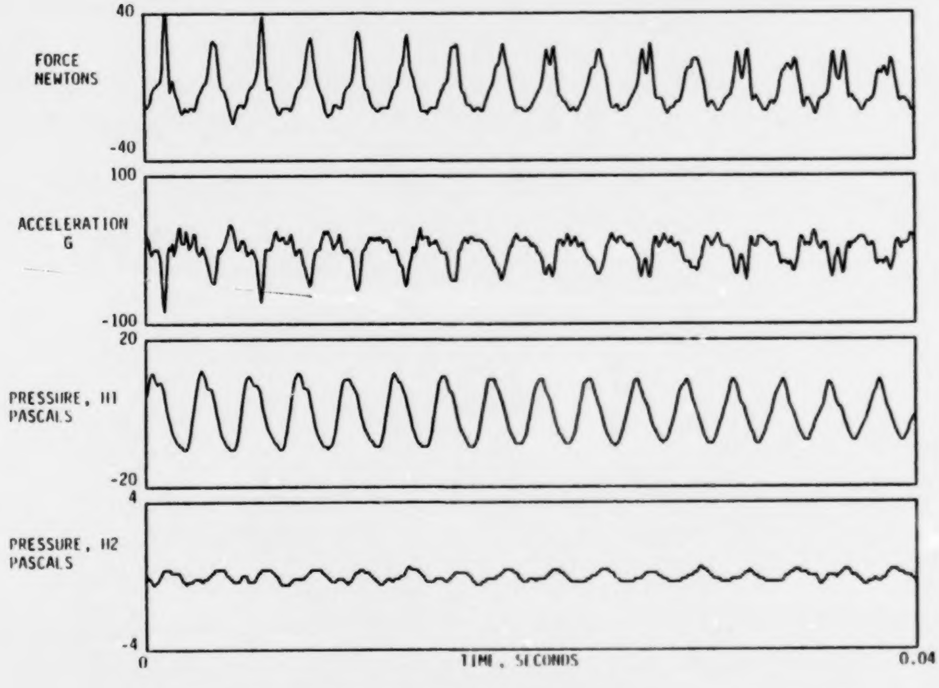


Figure 8. Signals Indicating Nonlinear Interaction Between Drive Piston and Soil Column.

the driving piston and the soil column. Note that the hydrophone signals appear more as sine waves. This is attributed to the higher attenuation of the harmonics as the acoustic signal propagates through the soil before reaching the hydrophones.

Test Cell

Two test cells, 3-in. ID (internal diameter) 4.0 and 6.0 in. height made of acrylic tubing, were used to hold the contaminated soil. The test cell used for decane tests was different from those tests of the zinc cell. A description of the two cells is provided below.

Decane Test Cell--

The test cell 3-in. internal diameter 4-in. height consists of two electrodes, the anode on top and the cathode at the bottom. A schematic of the decane cell is shown in Figure 9. The distance between the two electrodes is 2 in., which essentially is the sample cake thickness. The anode is a 3-in. diameter, 100 mesh stainless steel screen, whereas the cathode is a perforated s.s. supporting plate. The cathode is supported by four s.s. rods. A leachate collecting chamber was placed under the cathode. Leachate from the soil was drained through pipes to the leachate collecting pans.

Zinc Test Cell--

The test cell, 3 in. (internal diameter) x 6.0 in. (height) was designed for the purpose of flushing to maintain the moisture content of the soil. During the application of the electric field, electro-osmotic phenomena caused the water to move from the anode toward the cathode. This water movement would cause the layer in contact with the anode to become drier and thereby causing less ion movement since water is the medium in which ions transport. Since a medium is required to transport ions, the flushing design was devised.

More space was added to increase the distance between the anode and the cathode and to create two electrode-flushing chambers. The anode-flushing chamber is located at the top of the anode, whereas the cathode-flushing chamber is located at the bottom of the cathode, where the leachate is

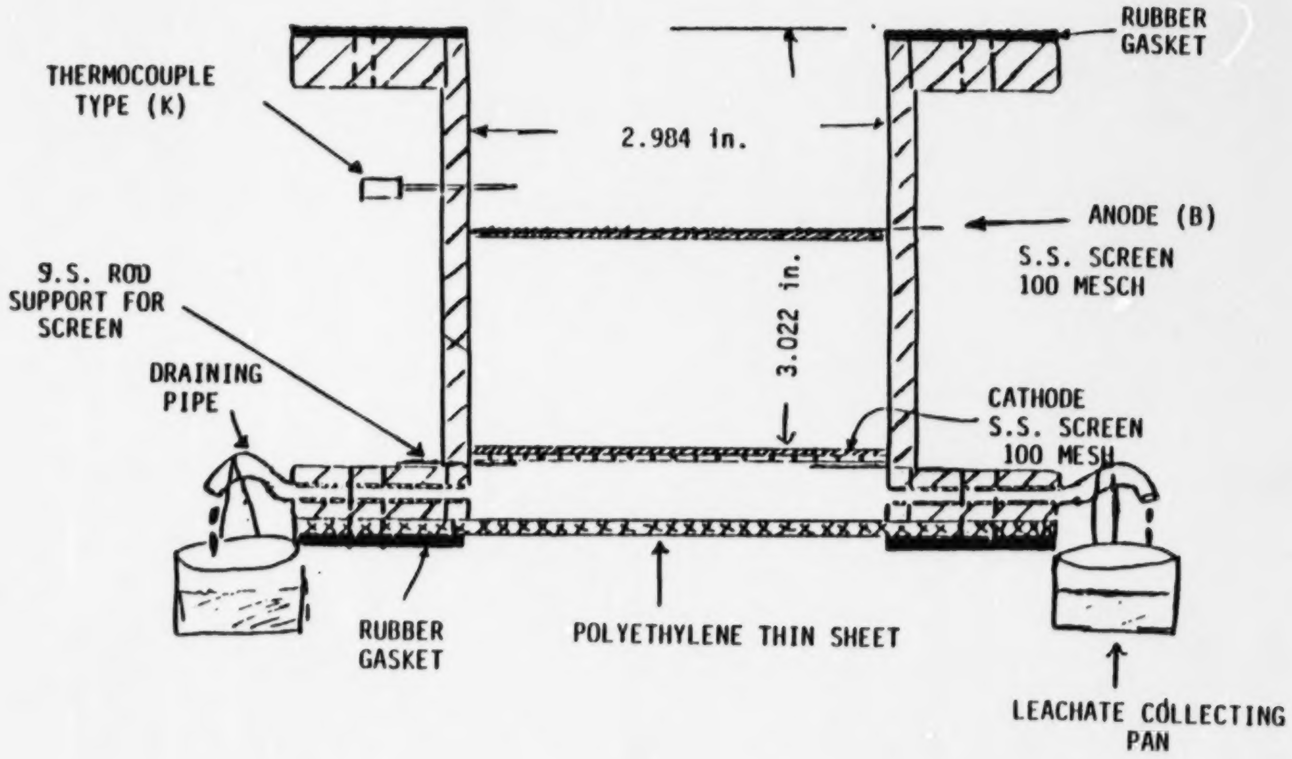

THERMOCOUPLE TYPE (K)
2.984 in.
RUBBER GASKET
ANODE (B)
S.S. SCREEN 100 MESCH
9.S. ROD SUPPORT FOR SCREEN
3.022 in.
DRAINING PIPE
CATHODE S.S. SCREEN 100 MESH
RUBBER GASKET
POLYETHYLENE THIN SHEET
LEACHATE COLLECTING PAN

Figure 9. Side View of Testing Cell for Electroacoustic Soil Decontamination Process Used for Decane Treatment.

collected. The distance between the anode and the cathode used in the zinc experiments is 4.5 in. The anode is a 3-in.-diameter perforated plate containing 1-mm-diameter holes and is connected to a spring-like lead to allow the anode to move with the cake and establish contact. The cathode is a 100-mesh s.s. screen supported by an s.s. perforated plate containing 4 mm diameter holes. Both screen and plate were supported by four s.s. rods, which criss-crossed under the perforated plate. Schematic of the zinc cell is shown in Figure 10.

EXPERIMENTAL PROCEDURES

The following experimental procedure is used in conducting the experimental investigation on both zinc and decane soil.

- Fill the bottom wood box with a known amount of saturated sand.
- Bolt the lower acrylic tubing on top of the box with a rubber gasket in between.
- Fill the lower acrylic tubing with saturated sand. The sand must be very wet and compacted to ensure acoustic coupling.
- Place a polyethylene plastic and rubber gasket sheet on top of the lower acrylic tubing.
- Place the testing cell on top of the polyethylene plastic sheet and bolt the cell to the lower acrylic tubing.
- Fill the leachate collecting chamber with distilled water until water starts to flow into the leachate collecting pans. During the zinc tests, the leachate draining pipes were connected to a peristaltic pump, which fed from a 500 mL beaker filled usually with about 350-400 mL distilled water. Water level was always maintained below the cathode during both decane and zinc tests.
- Place a known quantity of contaminated soil in the test cell on top of the cathode and leachate collecting chamber.
- Place the anode on top of the soil and exit connecting wire outside the cell.
- For the zinc tests the upper part of the test cell was modified for flushing purposes (Figure 5). The modification created a chamber above the anode which holds recycled water. The inlet tubing to the chamber is connected to a peristaltic pump, which feeds and recycles from a 500 mL beaker filled with about 350-400 mL deionized water.
- Place a polyethylene plastic and rubber gasket on top of the test cell, so that sand at field capacity of 9 percent moisture was always in contact with the anode.

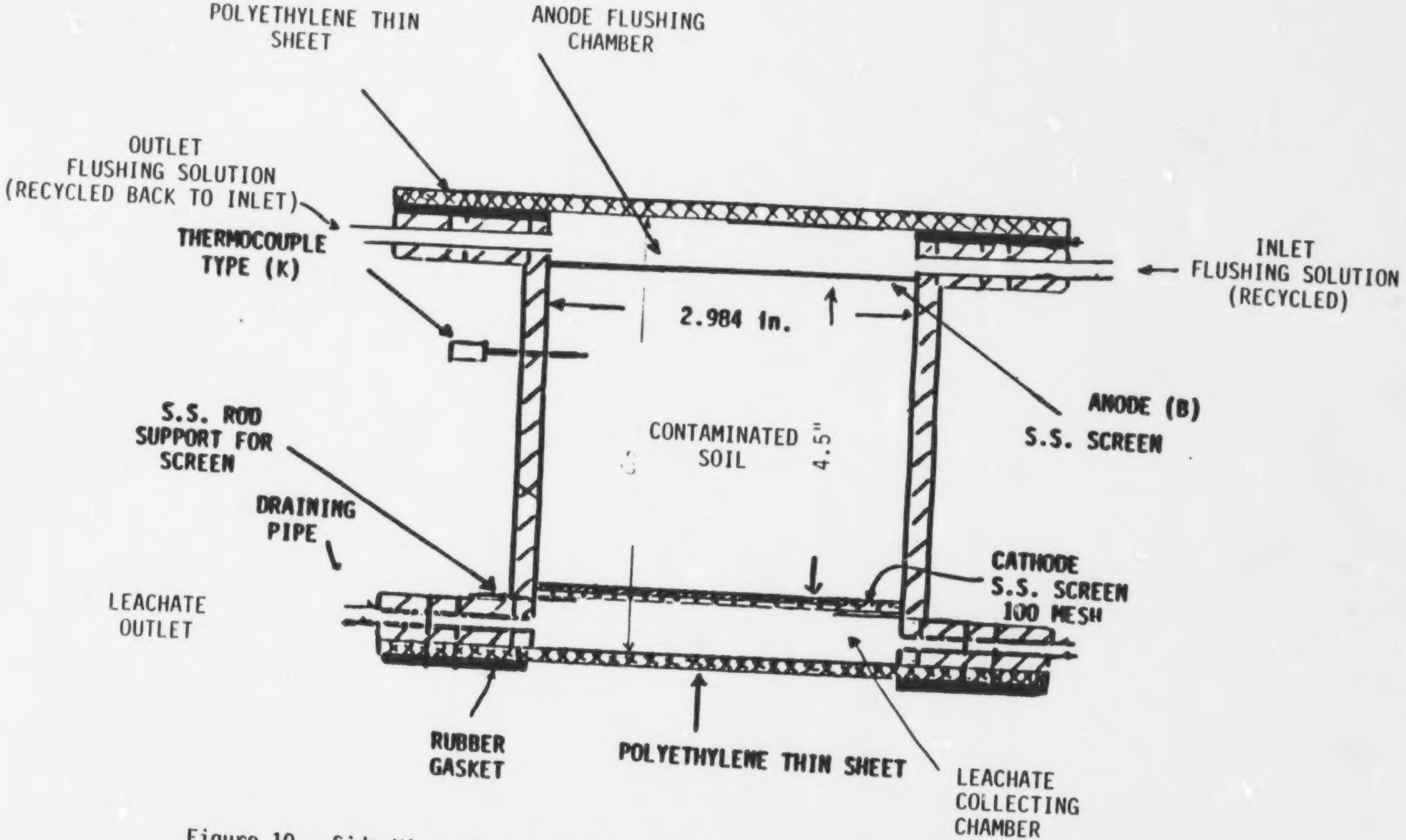

POLYETHYLENE THIN SHEET
ANODE FLUSHING CHAMBER
OUTLET FLUSHING SOLUTION (RECYCLED BACK TO INLET)
THERMOCOUPLE TYPE (K)
INLET FLUSHING SOLUTION (RECYCLED)
2.984 in.
CONTAMINATED SOIL
4.5"
ANODE (B) S.S. SCREEN
S.S. ROD SUPPORT FOR SCREEN
DRAINING PIPE
LEACHATE OUTLET
CATHODE S.S. SCREEN 100 MESH
RUBBER GASKET
POLYETHYLENE THIN SHEET
LEACHATE COLLECTING CHAMBER

Figure 10. Side View of Testing Cell for Electroacoustic Soil Decontamination Process Used for Zinc Soil, Zinc/Cadmium Soil Treatment.

- Bolt the upper acrylic tubing to the test cell.
- Fill the top acrylic tubing with wet sand.
- Connect the acoustic head to the acoustic driver (the acoustic head should be in contact with the sand).
- Insert the thermocouple inside the testing cell.
- Set the appropriate power input, acoustic power, and frequency and conduct the test for a given interval of time.
- During the test, the following variables were monitored: voltage, current, cake temperature, acoustic force, and acoustic acceleration.
- At the end of the test, turn off all the power sources.
- Weigh the treated cake and liquid leachate (zinc anode liquid and zinc cathode liquid).
- Save both leachate and cake in glass jar with Teflon sealing.
- Quarter and cone the samples in case of decane. In case of zinc, dry the sample at 105 C and 1 in. Hg for 24 hours, grind, and mix the sample.
- Send samples for analysis.

ANALYTICAL PROCEDURES

All the chemical analyses were performed according to the methods recommended in Test Methods for Evaluating Solid Waste, SW 846 (U.S. EPA, 1986). The atomic absorption spectroscopic method (flame AA - direct aspiration) was used to analyze zinc and cadmium. The zinc concentrations in leachate and soil were determined using Method 7950. Cadmium in leachate and soil was analyzed by Method 7130. For sample preparation, Method 3010 was used with leachate and Method 3050 with soils. The samples were digested using nitric acid, hydrochloric acid, and hydrogen peroxide. The analyses were performed on Perkin-Elmer Model 5000AA using an oxidizing air/acetylene flame.

Decane analyses were performed using gas chromatographic methods. Soxhlet extraction procedure (Method 3540 in SW 846) was used in the sample preparation and during extraction of decane from the soil. Here, 1:1 v/v mix of pesticide-grade hexane and acetone was used as the extraction solution. Extracts were concentrated using the standard Kuderna Danish apparatus. The analyses were performed on a Hewlett-Packard Model 5890A gas chromatograph by flame ionization detection. The column used was Supelco SPB-5, 30 m long, 0.5 mm ID, and 1.5 ppm phase thickness. The temperature program was 100 C initially and ramped at 10 C/min without initial hold. Once the temperature reached 250 C, it was held for 10 min. The injector and detector temperatures were 230 and 250 C, respectively. Carrier gas and flame ionization detector make up gas were nitrogen. Combustion support gases were air and hydrogen. Sample injection volume was 1/mL and was performed by an HP Model 7673 autoinjector. Data were collected by an HP Model 3396 integrator.

All the chemical analyses were performed by Zande Environmental Laboratories, Columbus, Ohio. For quality-control purposes, some samples from the same batch were sent to the U.S. EPA's Risk Reduction Engineering Laboratory for chemical analyses.

The soil samples were analyzed for particle-size distribution, as recommended by V. J. Kilmer and L. T. Alexander (1949, Methods of Making Mechanical Analyses of Soils. Soil Science 68:15-24). Each soil sample was dispersed in a sodium hexametaphosphate and sodium carbonate solution. The <20 μ, <5 μ, and <2 μ fractions were determined by pipetting after sedimentation. The <0.2 μ fraction was determined by pipetting after centrifugation. Sand was separated from silt and clay by washing the sample through a 300-mesh sieve. The various sand fractions were determined by dry sieving and weighing.

Organic carbon content in soil was determined by the dry-combustion method. This involved combusting approximately 2 gal. of soil at 900-950 C in oxygen gas stream. Carbon dioxide generated was absorbed by ascarite bulb. The organic carbon content in soil was estimated from the amount of CO_2 generated.

SECTION 5

EXPERIMENTAL RESULTS

Batch experimental results for both decane and zinc are discussed below. The following ESD parameters were investigated.

- Effect of electric field on decane mobility
- Effect of voltage and time on decane removal
- Effect of acoustic power and frequency.

DECANE EXPERIMENTAL RESULTS

A total of 30 decane tests were conducted to establish the technical feasibility for decane removal via ESD. Tests 1 through 9 were shake-down tests. For Tests 10 through 25, the treated soil samples were mixed thoroughly and sent for analysis to both labs. These tests were designed to monitor the decane removal. Results are shown in Appendix A. Tests 26 through 30 were designed to monitor the decane mobility and removal. The treated soil samples for each test were divided into three layers (Figure 11). Then each layer was quartered as shown in Figure 12. Two quarters were sent to the U.S. EPA laboratory and the other two quarters were sent to Zande Laboratory.

Initial Decane Concentration

The soil sample was contaminated at Battelle by adding 8 weight percent decane, dry basis (D.B.) into the soil. However, since the soil favors the absorption of water over decane and since the soil was saturated with water, all of the 8 percent did not go into the soil. Five soil-decane samples were taken from the mixture for laboratory analysis. Soil analysis by Zande Labs, Columbus, Ohio, showed an average of 5.14 percent (D.B.) present in the soil. However, Test 15 (control - no ESD) soil shows 6.42 percent decane for the

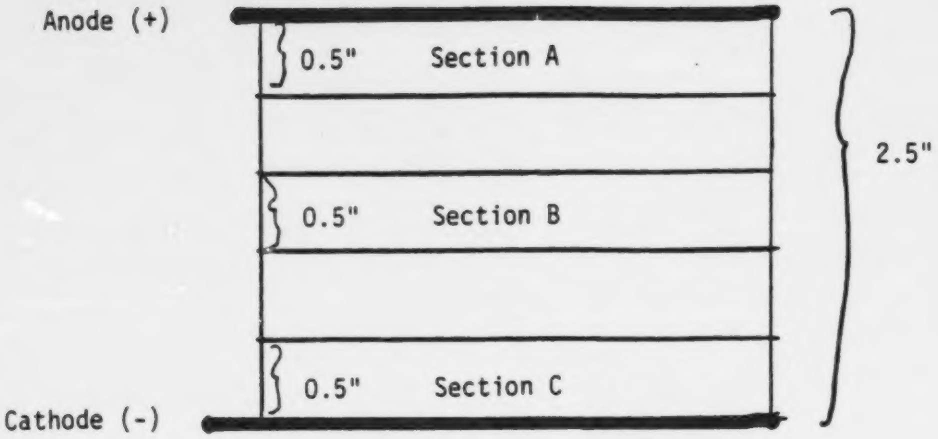

Anode (+)
0.5"
Section A
2.5"
0.5"
Section B
0.5"
Section C
Cathode (-)

Figure 11. Side View of the Treated ESD Cake in Decane Tests (26D, 27D, 28D, and 30D) Showing the Three Analyzed Layers.

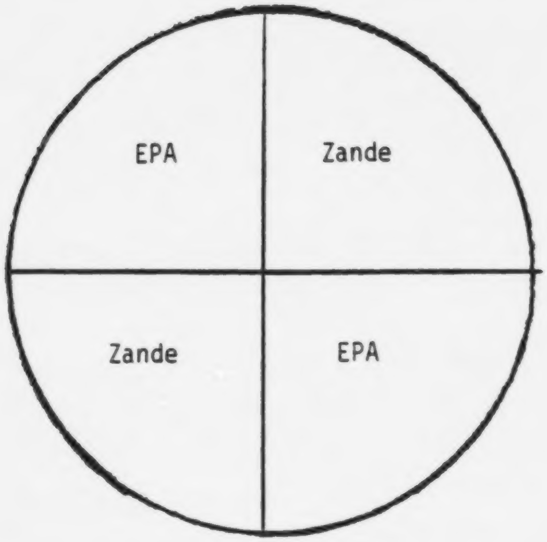

EPA
Zande
Zande
EPA

Figure 12. Top View of Decane Layer Showing How the Layer Was Divided and Analyzed.

same mixed soil analyzed by the same laboratory. This discrepancy in the initial decane concentration in the soil made subsequent data analysis very difficult. Test Sample 15D (control) was analyzed by both Zande Labs and the U.S. EPA Laboratory. The analytical results were 6.36 and 6.48, respectively. Since the laboratory analysis on decane concentration for Test 15 match the U.S. EPA decane analysis, it was decided to take the Test 15 decane concentration as the reference for initial decane concentration in the soil. Table 5 shows Zande Labs data for initial decane concentration in the soil before correction and after correction. The initial solids content of the decane soil was 52.8 percent.

Effect of Electric Field on Decane Mobility

When a d.c. electric field is imposed against a porous soil medium, migration of water occurs toward the cathode. This phenomenon, called electro-osmosis, refers to the migration of ions that have the ability to compensate the charges on the soil toward the opposite charged electrodes. Water is transported during this phenomenon by ions because of viscous interactions, water of hydration, and molecular collisions. We hypothesized that, since decane is hydrophobic and lighter than water, the decane would co-transport with water during electro-osmotic transport. However, our experimental results do not completely validate this theory. However, as shown in Table 8, results of Tests 26 through 30 indicate that there seems to be a trend for the movement of the decane from the top anode layer toward the cathode layer and the movement of water is also in the same direction. Thus, the results indicate that there is a potential for the transport of organics in aqueous suspensions in the presence of d.c. electric fields. This effect can possibly be further enhanced by using appropriate additives, such as dispersants used in tertiary oil recovery by the petroleum industry.

Effect of Electric Field and Time on Decane Removal

The following electrical and time parameters were investigated:

- Voltage (0, 12.5, 25, 37.5, V/in.)
- Time (1.25, 2, 24.0 hours).

TABLE 8. EFFECT OF ELECTRIC FIELD ON THE DECANE MOBILITY

Test No.	Voltage volts/in.	Acoustic Power Watts	Layer	EPA Decane (%) Wet Basis	% Decane Removal $\frac{\text{Layer A - Layer ()}}{\text{Layer A}} \times 100$
26	37.5	0	Layer A	4.45	0
			Layer B	4.3	3.49
			Layer C	3.9	12.36
27	45	0	Layer A	4.35	0
			Layer B	4.17	4.16
			Layer C	3.56	18.16
28	25	0	Layer A	4.29	0
			Layer B	4.07	5.13
			Layer C	3.34	22.14
30	37.5	0	Layer A	4.44	0
			Layer B	3.90	12.16
			Layer C	3.54	20.27

The analytical results for decane tests were inconsistent. Zande Lab analyses for decane concentration in soil samples were higher than those of the U.S. U.S. EPA. This inconsistency made it difficult to reach a firm conclusion about the percent decane removal resulting from the electric field on ESD and time. However, based on the tests (14D, 15D, 17D, 21D, 22D, and 23D) in which the decane values from the two labs were relatively close, the data indicated about 10-25 percent decane removal. For example, Test 15D (control test, no ESD) showed an average 6.42 percent decane in the soil, whereas Test 17D (in which the electric field/acoustic was applied at 12.5 V/in., 0.6 W, 2 hour) showed a decane removal of 20.25 percent (from Zande) to 25.7 percent (from U.S. EPA Laboratories). The average of the two analyses is 22.9 percent decane removal. Since most of the tests were done for a short time (less than 25 hours), one expects a larger decane removal if ESD were applied for longer periods with the flushing and added dispersant. However, more tests are needed to validate the above assumption.

Effect of Electric Field on Soil Moisture Content

The electro-kinetic potential across the soil is the driving force of electro-osmotic dewatering. As discussed previously, water moves from the anode toward the cathode. This movement of water causes the moisture content of the soil to change. The layer in contact with anode is always drier. This phenomena can be seen clearly for the decane soil Tests 26D, 27D, 28D, and 30D. For example, in Test 27, the cake in contact with anode had a moisture content of 27.35 percent, the cake between the anode cake and the cathode cake had a moisture content of 38.76 percent, and the cake in contact with cathode had moisture content of 49.42 percent. The initial moisture content for the soil before ESD treatment was 47.32 percent. Figure 13 shows cake moisture as a function of cake gradient.

Effect of Acoustic Field

The analytical results for the decane tests had high variability, as mentioned earlier. Therefore, the effectiveness of the electric fields with

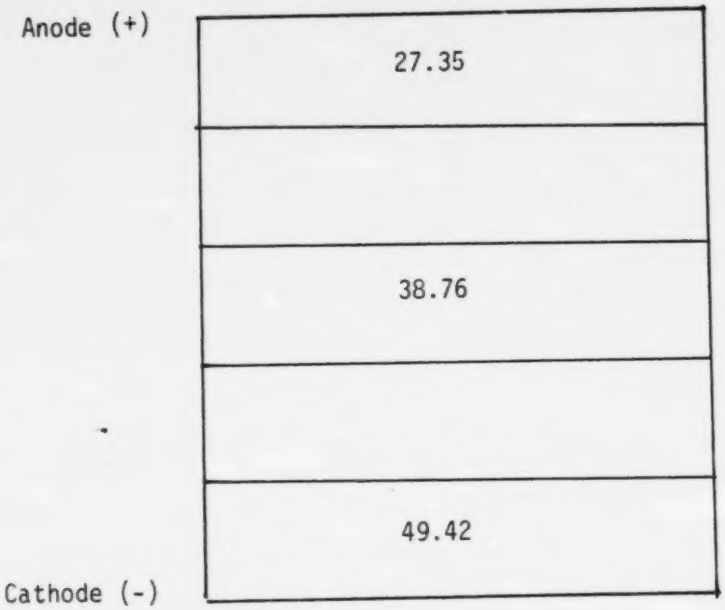

Anode (+)
27.35
38.76
49.42
Cathode (-)

Figure 13. Side View of Decane-Treated ESD Cake Showing Layer Moisture Content.

or without an acoustic field is difficult to accurately detect. The highest estimate of removal is 30 percent. Acoustics has always been applied as an enhancement to electric field in which the rate of removal is increased with some increase of overall removal. But, because of the low removal rate of the electric field and high variability of the analytical results, and the fact that no rate information was obtained, no acoustical effects can be observed.

This is not to say there is no acoustic effect; there indeed may be a positive effect, but it cannot be "observed" in the relatively few number of tests with highly variable results.

Statistical Analysis on Tests 26D-30D

A statistical analysis was performed on Tests 26D-30D laboratory result from both U.S. EPA and Zande Lab. Analysis shows that there doesn't appear to be any relationship between the decane concentration measured by the two laboratories. The correlation between the 15 measurements made between the two laboratories was calculated to be 0.233. A correlation of zero would indicate that there is no linear relationship between the two measurements, whereas a correlation of 1 or -1 would indicate that there is a perfect linear relationship between the two sets of measurements. The sample correlation of 0.233 was not statistically significantly different from zero; thus, there is no relation between the two laboratories' data. Moreover, a statistical comparison of the decane concentration measured by the two laboratories shows that the measurements made by Zande tend to be an average 2.94 percent higher than the measurements made by the U.S. EPA.

The 95 percent confidence interval for the average difference in the measured decane concentrations ranges from 2.35 to 3.53 percent. This means that we are 95 percent confident that individual differences between U.S. EPA and Zande measurement fall between a minimum difference of 2.35 and a maximum difference of 3.53 percent. Table 9 shows statistical regression output for each test and an overall regression output on all the measurement points in Test 26 through Test 30. The statistical output (standard error of estimate, number of points used, standard error of coefficient, and root mean squared) show a very poor correlation between U.S. EPA and Zande data. For example,

TABLE 9. STATISTICAL ANALYSIS RESULTS FOR DECANE TESTS

Test Number	Decane Results		Statistical Regression Output		
	EPA (%)	Zande (%)			
26DA	5.38	9.11	26D Regression output:		
26DA1	5.29	8.89	Constant		11.72677
26DA2	6.04	7.90	Std Err of Y Est		.4968266
26DB	6.07	8.40	R Squared (Adj, Raw)	- .019976	.2350181
26DC	6.29	8.92	No. of Observations		5
			Degrees of Freedom		3
			Coefficient(s)	- .530103	
			Std Err of Coef.	.5521724	
27DA	5.99	8.91	27D Regression output:		
27DB	6.81	8.51	Constant		-2.11666
27DC	7.04	11.64	Std Err of Y Est		1.972165
			R Squared (Adj, Raw)	- .333129	.3334356
			No. of Observations		3
			Degrees of Freedom		1
			Coefficient(s)	1.785111	
			Std Err of Coef.	2.523948	
28DA	6.10	8.43	28D Regression output:		
28DA	6.10	10.31	Constant		30.18886
28DB	6.20	7.59	Std Err of Y Est		1.248483
28DC	5.58	10.49	R Squared (Adj, Raw)	.2280125	.4853417
			No. of Observations		4
			Degrees of Freedom		2
			Coefficient(s)	-3.50094	
			Std Err of Coef.	2.549209	

TABLE 9. (CONTINUED)

Test Number	Decane Results		Statistical Regression Output		
	EPA (%)	Zande (%)			
30DA	6.02	8.27	30D Regression output:		
30DB	5.73	8.73	Constant		15.17859
30DC	5.77	8.36	Std Err of Y Est		.2439200
			R Squared (Adj, Raw)	.0346422	.5173211
			No. of Observations		3
			Degrees of Freedom		1
			Coefficient(s)	-1.15202	
			Std Err of Coef.	1.112784	
MEAN	6.03	8.96	OVL DRY Regression output:		
S.D.	.45	1.04	Constant		5.764438
			Std Err of Y Est		1.081622
			R Squared (Adj, Raw)	-.018986	.0537989
			No. of Observations		15
			Degrees of Freedom		13
			Coefficient(s)	.5307563	
			Std Err of Coef.	.6173460	
			26DA Regression output:		
			Constant		10.86250
			Std Err of Y Est		.1539435
			R Squared (Adj, Raw)	.8587125	.9293563

0.0537 root squared (raw) for the overall data shown at the end of Table 8 indicate that only 5.37 percent of the data fit the correlation. The difference between the U.S. EPA measurements and Zande measurements and their descriptive statistics are contained in Table 10. Also, Figure 14 shows Zande measurements against U.S. EPA measurements.

QC Assurance of Analytical Data: Decane

All the analytical data for decane in soil samples used in the ESD tests are given in Table 11. It is apparent that the analytical results were inconsistent for the two laboratories. For example, the variation of interlaboratory results ranged from 0.62 to 64.71 percent. However, the quality control tests performed by both laboratories indicate significant precision and accuracy of their data. For example, Sample 26DA was analyzed in triplicate by both laboratories (see Table 10). Percent variations were »8.5 and »5 for U.S. EPA and Zande Laboratories, respectively. Recovery data given in Table 12 show that the average percent recoveries were within 75 to 125 percent. Because of these conditions, it is difficult to determine the inaccuracies in analytical results. The differences in interlaboratory analytical results may be attributed to oversaturation of samples with decane, nonuniformity of sample, incomplete mixing, and differences in laboratory analytical execution. Consequently, it was decided to use only the analytical data that have interlaboratory variations of less than 15 percent to determine the effectiveness the ESD process is in decane removal.

It is recommended that further investigations be conducted by U.S. EPA to improve the analytical methodologies for organic contaminants in soil samples. Inconsistencies in analytical results as indicated in our study can have a significant impact in the development of innovative treatment processes and improvement of existing treatment technologies.

TABLE 10. EPA AND ZANDE MEASURED DECANE CONCENTRATIONS AND THEIR DIFFERENCES IN SOIL (DRY BASIS)

Test Number	EPA (%)	Zande (%)	Difference (%)
26DA	5.380	9.110	3.730
26DA1	5.290	8.890	3.600
26DA2	6.040	7.900	1.860
26DB	6.070	8.400	2.330
26DC	6.290	8.920	2.630
27DA	5.990	8.910	2.920
27DB	6.810	8.510	1.700
27DC	7.040	11.640	4.600
28DA	6.100	8.430	2.330
28DA	6.100	10.310	4.210
28DB	6.200	7.590	1.390
28DC	5.580	10.490	4.910
30DA	6.020	8.270	2.250
30DB	5.730	8.730	3.000
30DC	5.770	8.360	2.590
Number of Samples	15	15	15
Minimum	5.290	7.590	1.390
Maximum	7.040	11.640	4.910
Mean	6.027	8.964	2.937
Standard Dev	0.468	1.071	1.064

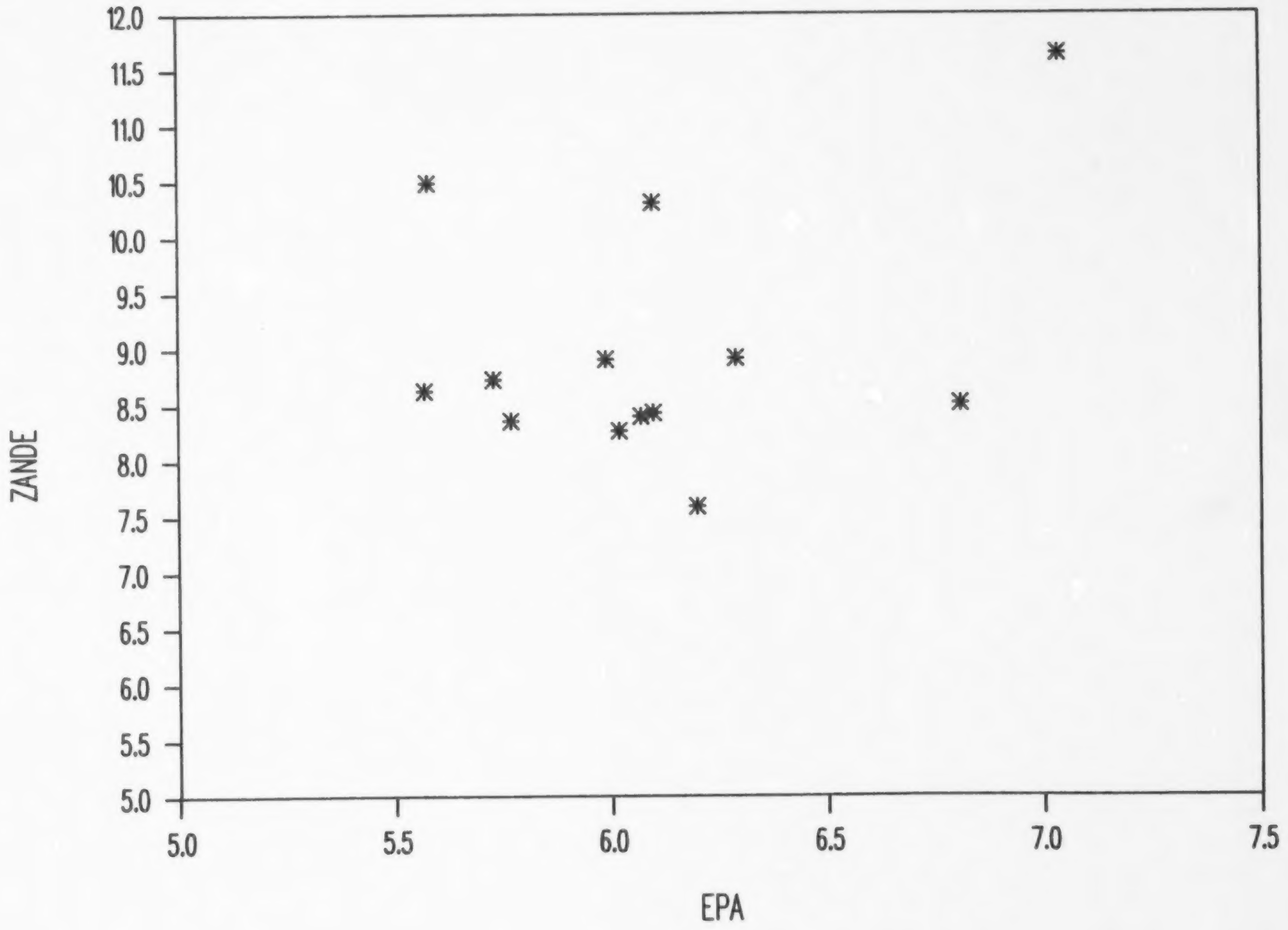


FIGURE 14. Zande Measured Decane Concentration Plotted Versus U.S. EPA Measured Concentration.

TABLE 11. COMPARATIVE ANALYTICAL DETERMINATION OF DECANE IN SOILS BY U.S. EPA AND ZANDE LABORATORIES

Test No.	EPA Decane Concentration Dry Basis	Zande Decane Concentration Dry Basis	Percent Variability Zande and U.S. EPA
10D	1.17	5.46	64.71
11D	4.23	5.59	13.85
12D	2.77	5.14	29.96
13D	4.79	5.08	2.94
14D	4.78	5.63	8.17
15D	6.48	6.36	0.62
17D	4.77	5.12	3.54
19D	4.93	3.75	13.59
20D	4.98	3.57	16.49
21D	5.6	6.1	4.27
22D	5.28	6.75	12.22
23D	6.22	6.58	2.81
26DA*	5.57	8.64	21.60
26D	6.07	8.40	16.10
26DC	6.29	8.90	17.18
27DA	5.99	8.91	19.53
27DB	6.81	8.51	11.09
27DC	7.04	11.64	24.63
28DA	6.10	9.37	21.14
28DB	6.20	7.60	10.14
28DC	5.58	10.49	30.55
30DA	6.02	8.27	15.75
30DB	5.13	8.73	25.97
30DC	5.77	8.36	18.33

*For example, percent variability was calculated as follows:

For 10D $$\frac{5.46 - 1.17}{5.46 + 1.17} \times 100 = 64.7\%$$

TABLE 12. QC DATA FOR EPA ANALYSES

Sample ID	Amount Spike Added (ppg)	Amount Spike Removed (ppg)	Percent Recovery
14D	10,000	7,700	77
	10,000	7,300	73 (duplicate)
19D	200,000	202,000	101
	200,000	165,200	82.6 (duplicate)

ZINC TESTS

Results of zinc tests, background on electro-chemical reactions of zinc at electrode and other related discussion is presented in the following paragraphs.

Results of Zinc Tests

A total of 16 tests were conducted on the zinc-contaminated soil. Results of these tests are shown in Appendix B. The first six tests (1Z-6Z) were conducted to establish the standard procedures, such as flushing or sectioning; for example, no sectioning was used in Tests 3-4.

The treated soil was mixed (cake in contact with anode was mixed with cake in contact with cathode) and sent for lab analysis. Lab analysis did not show any zinc removal. However, in Tests 5-6, the treated cake was divided in half (cake in contact with anode and cake in contact with cathode). Results show that over 80 percent average removal of the zinc was achieved in the anode layer and some zinc accumulation in the cathode cake.

Background on Electro-chemical Reactions of Zinc at the Electrode

During the application of d.c. electric field, electrolysis of water in the soil occurs with the following reaction $H_2O \text{ Å } H^+ + OH^-$. The $(OH)^-$ ions at the cathode combine with cations to form appropriate compounds based on their relative concentrations. Simultaneously, the pH at the cathode increases. The zinc accumulation around the cathode is due to an increase in the soil pH. Zinc is soluble at pH below 6. Above pH 6, zinc would exist as $Zn(OH)_2$, $ZnOH+$, $ZnOHCl$, and ZnO_2, which are insoluble in water. Since the soil around the cathode is basic (pH value of 9-11), the zinc will precipitate in the layer around the cathode. Figure 15 shows the solubility of zinc as a function of pH. The diagram shows zinc ion Zn^{+2} become insoluble at pH between 8-9. Also, we have calculated the percentage of zinc ions and their complex forms at different pH. The calculations were performed using the geochemical computer code MINTEQA2 (developed for U.S. EPA, 1988). The code calculates the distribution of chemical species (ions, neutral species, and

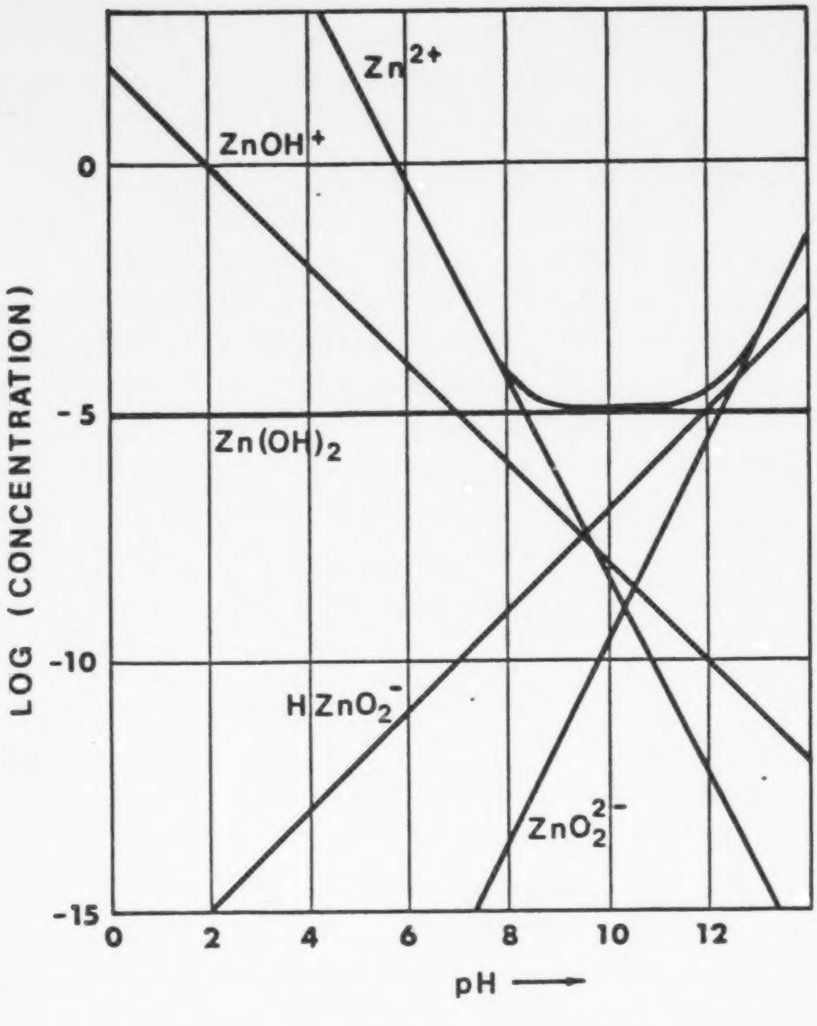


Figure 15. The Amphoteric Nature of ZnO is Revealed in the Variety and Solubility of the Ionic Species, which the Oxide Displays on Dissolving in Water at Various pH Values(33).

ion-pairs) in a water system for total analytical concentration, pH, and Eh data. In addition, the code may be used to compute in detail the changes in fluid composition, the identity and the extent of precipitation or dissolution of secondary minerals. Table 13 shows calculation for percent distribution at pH 6 and 9.7. A more detailed analysis is listed in Appendix C. Since there was zinc accumulation in the cake toward the cathode, it was decided to divide the ESD treated soil into the following four sections:

- ZA - Soil in contact with anode (1 in. thick)
- ZD - Soil in contact with anode layer (1 in. thick)
- ZC - Soil in contact with cathode layer (1 in. thick)
- ZB - Soil in contact with cathode (1 in. thick)

A schematic of the four sections is shown in Figure 16. Also, it was observed in Test 3 and 4 that the moisture content of the layer in contact with anode was always decreasing, thereby, reducing the ion transport efficiency. Hence, it was decided to modify the test cell so the anode layer can be flushed with water to maintain its moisture consistency and, thus, to provide a transport medium for the zinc ions. A schematic of the modified cell is shown in Figure 10.

The following ESD parameters were investigated:

- Leaching time
- Electrical power
- Acoustic power
- Acoustic frequency.

A mass balance on Test 16Z is shown in Table 14. Mass balance data show that all of the zinc was accounted for. Initial zinc weight in the soil (before ESD) is 0.818 g whereas total zinc weight in cake layers and leachate after ESD totaled 0.819 g. No zinc was lost, which correlates well between experimental and analytical data for that test. Only Test 16Z leachate was sent for analysis. Other tests mass balance might show loss resulting from analytical variation.

Effect of Time on Zinc Removal

The ESD time is one of the critical parameters for the zinc ion removal. Figure 17 shows percent zinc removed as a function of cake gradient for 25 and 100 hours at power input of 0.510 and 0.390 W, respectively. The data shows

TABLE 13. PERCENT IONIC DISTRIBUTION FOR $ZnCl_2$ AT PH 6 AND 7

	pH 6	pH 7
	Percent Distribution	
Zn^{+2}	94.0 Zn^{+2} 5.7 $ZnCl^+$	73.9 $Zn(OH)_2$ 25.3 $Zn(OH)_3^-$
Cl^-	96.7 Cl^{-1} 3.1 $ZnCl^+$	99.9 Cl^{-1}
H_2O	48.9 ZnOHCl 50.1 $ZnOH^+$	1.5 OH^- 64.2 $Zn(OH)_2$ 33.0 $Zn(OH)_3^-$ 1.2 $Zn(OH)_4^{-2}$
H^{+1}	48.9 ZnOHCl 50.1 $ZnOH^+$	15.25 ZnOHCl 17.83 OH^- 13.42 $ZnOH^+$ 17.83 $Zn(OH)_2$ 17.83 $(OH)_3^-$ 17.83 $Zn(OH)_4^{-2}$

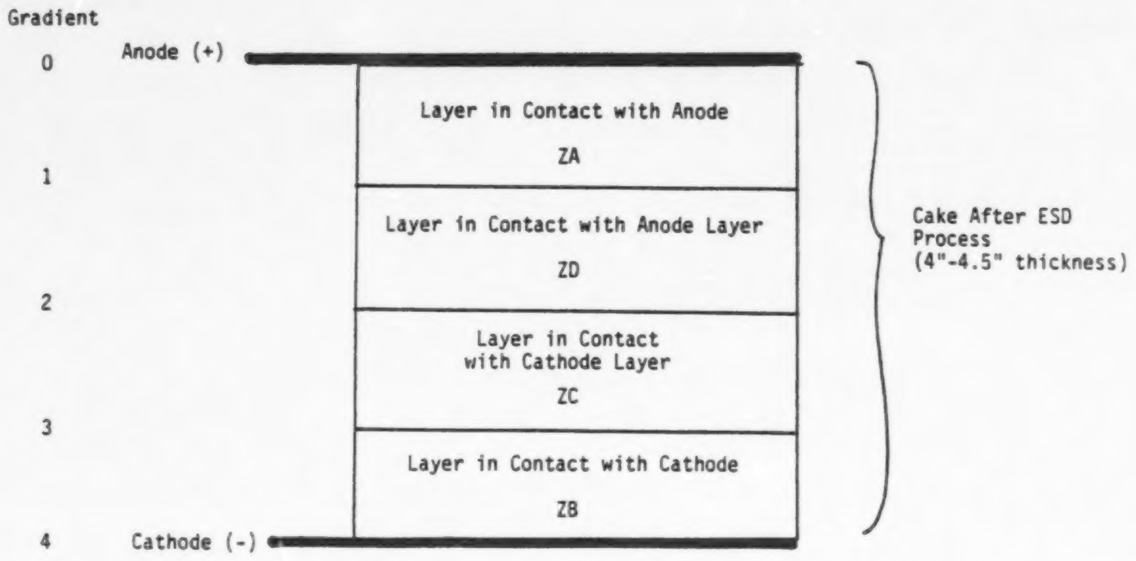
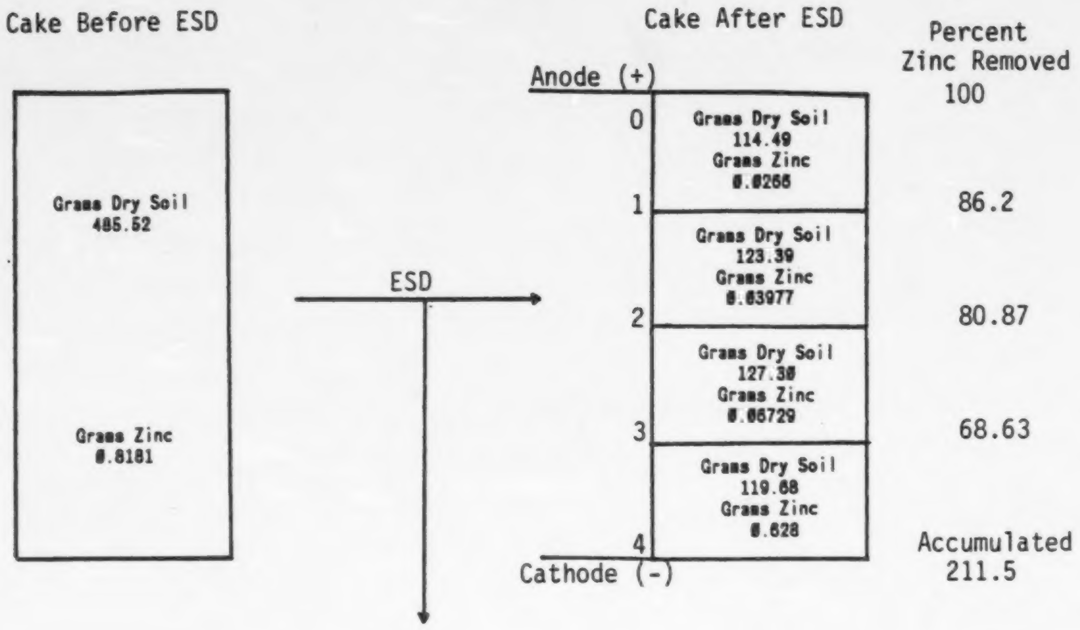

Gradient
0
1
2
3
4
Anode (+)
Cathode (-)
Layer in Contact with Anode
ZA
Layer in Contact with Anode Layer
ZD
Layer in Contact with Cathode Layer
ZC
Layer in Contact with Cathode
ZB
Cake After ESD Process (4"-4.5" thickness)

Figure 16. Schematic of the Cake-Divided Sections for Test 7Z-167.

TABLE 14. SAMPLE MASS BALANCE AROUND THE ZINC FOR TEST #16Z


Cake Before ESD
Grams Dry Soil
485.52
Grams Zinc
0.8181
ESD
Cake After ESD
Percent
Zinc Removed
Anode (+)
0
Grams Dry Soil
114.49
Grams Zinc
0.0266
100
1
Grams Dry Soil
123.39
Grams Zinc
0.03977
86.2
2
Grams Dry Soil
127.30
Grams Zinc
0.06729
80.87
3
Grams Dry Soil
119.68
Grams Zinc
0.628
68.63
4
Cathode (-)
Accumulated
211.5

Zinc weight in leachate = 0.0577 g

Mass Balance Around the Zinc

Initial zinc concentration in the soil = 0.001685 g zinc/g dry soil

Zinc weight in the soil before ESD = 485.52 x 0.001685
= 0.818 g

Zinc weight in the cake after ESD = (114.49) (0.0002325) + (123.39) (0.0003223) + (127.30) (0.0005286) + (119.68) (0.005248)

= 0.02662 + 0.03977 + 0.06729 + 0.62808

= 0.76176

Zinc weight in the leachate after ESD = 0.0577 g

Total zinc weight after ESD = Zinc weight in the soil and zinc weight in leachate.
= 0.76176 + 0.0577
= 0.819 g

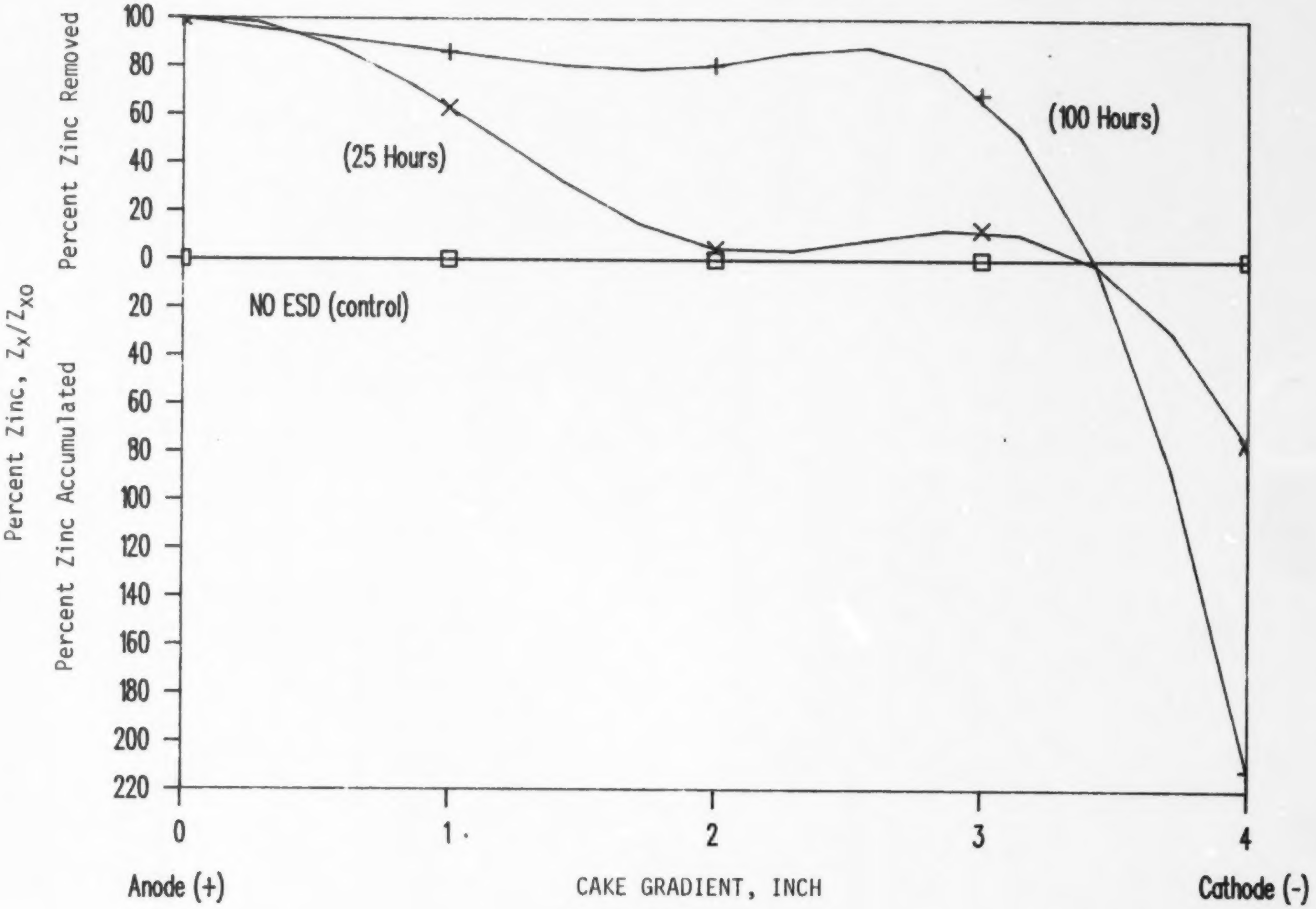


Figure 17. Variation of Percent (Wt) Zinc Removed/Accumulated as a Function of Cake Gradient for 25 and 100 Hours' Leaching Time.

the longer the ESD time, the higher the zinc removal in all layers except the layer adjacent to the cathode. For example, in cake gradient 1, at 100 hours, there was 86.2 percent zinc ion removal, whereas at 25 hours in the same layer under similar experimental conditions, zinc ion removal was 63 percent.

In cake gradient 2 at 100 hours, the percent zinc removal was 80.87, whereas at 25 hours, the percent zinc removal was only 4.5 percent. Table 15 shows a schematic of comparative actual concentrations of zinc ions in each cake gradient. During the 25-hour run, approximately 1063 ppm of zinc was transported across the cake length. However, during the 100-hour run, the total amount of zinc transported was 1485 ppm. This suggests that it took 75 hours to transport the extra 322 ppm from cake gradient number 1. From the figure, it can be inferred that the transfer efficiency of ions decreases with increasing time. This perhaps may be due to dynamic changes in the concentration of those ions in that particular cake gradient. Conventional techniques such as pump and treat normally require 2-3 years for an acceptable cleanup period in a sandy soil. Treatment time of 100 hours to reduce the concentration levels to less than 85 percent by ESD appears extremely beneficial.

Effect of Average Power on Zinc Removal

As discussed earlier in the decane section, electro-kinetic potential across the contaminated soil is the driving force for electro-osmotic rate. The current that is created by this potential is a function of electro-kinetic property of the material, such as conductivity and pH. Both current and voltages have a significant effect on zinc ion removal. Data in Figure 18 show the higher average power consumed, the more zinc was removed in each layer at constant ESD time at cake gradient 1 and 50 hour ESD (one inch from the anode). A total of 89.73 percent zinc was removed at an average consumed power of 0.811 W whereas at 0.114 Watts, 60.18 percent of the zinc was removed, and, at 0.013 W, 30.25 percent zinc was removed. Moreover, the data clearly indicate that zinc ions are accumulating at the cathode because of the high alkalinity of the soil (pH 9-11). Figure 19 shows actual zinc concentration as a function of cake gradient at three average powers for 50-hour tests. For the 100-hour tests, much higher zinc removal was achieved at a power of 1.423 W than at power of 0.390. However, the efficiency (kW/equiv.

TABLE 15. ZINC CONCENTRATION AT DIFFERENT CAKE GRADIENT FOR DIFFERENT LEACHING TIME

	Electric Time (hours)			
	0	25	50	100
0 Anode (+)	Zinc Concentration (ppm)			
1	1685	622	166	232
2	1685	1608	585	322
3	1685	1471	1858	528
4 Cathode (-)	1685	2965	4513	5250

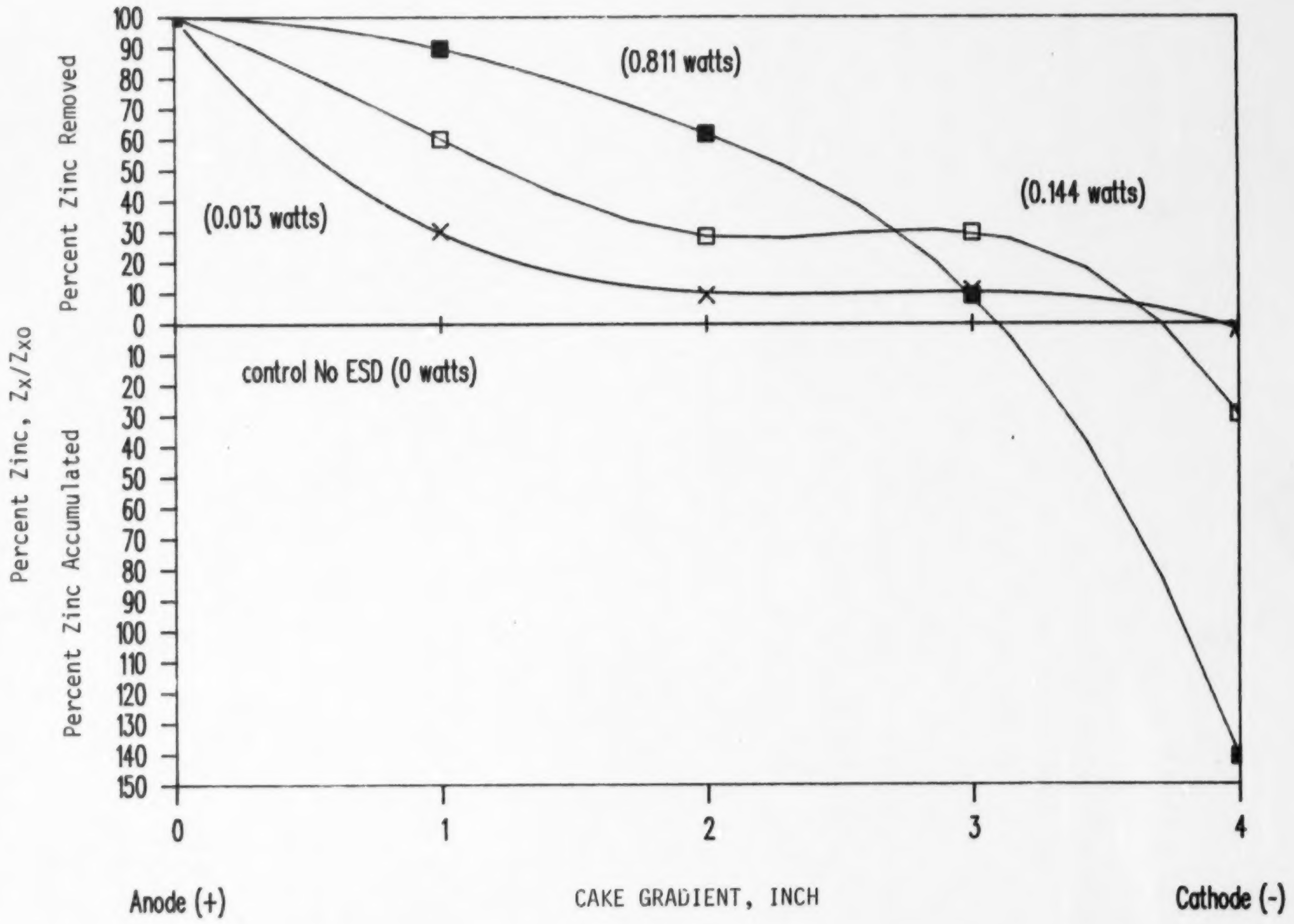


Figure 18. Variation of Zinc (Wt%) Removed/Accumulated as a Function of Cake Gradient for 0, 0.013, 0.144, and 0.811 Average Power Input for 50 Hours' Leaching Time.

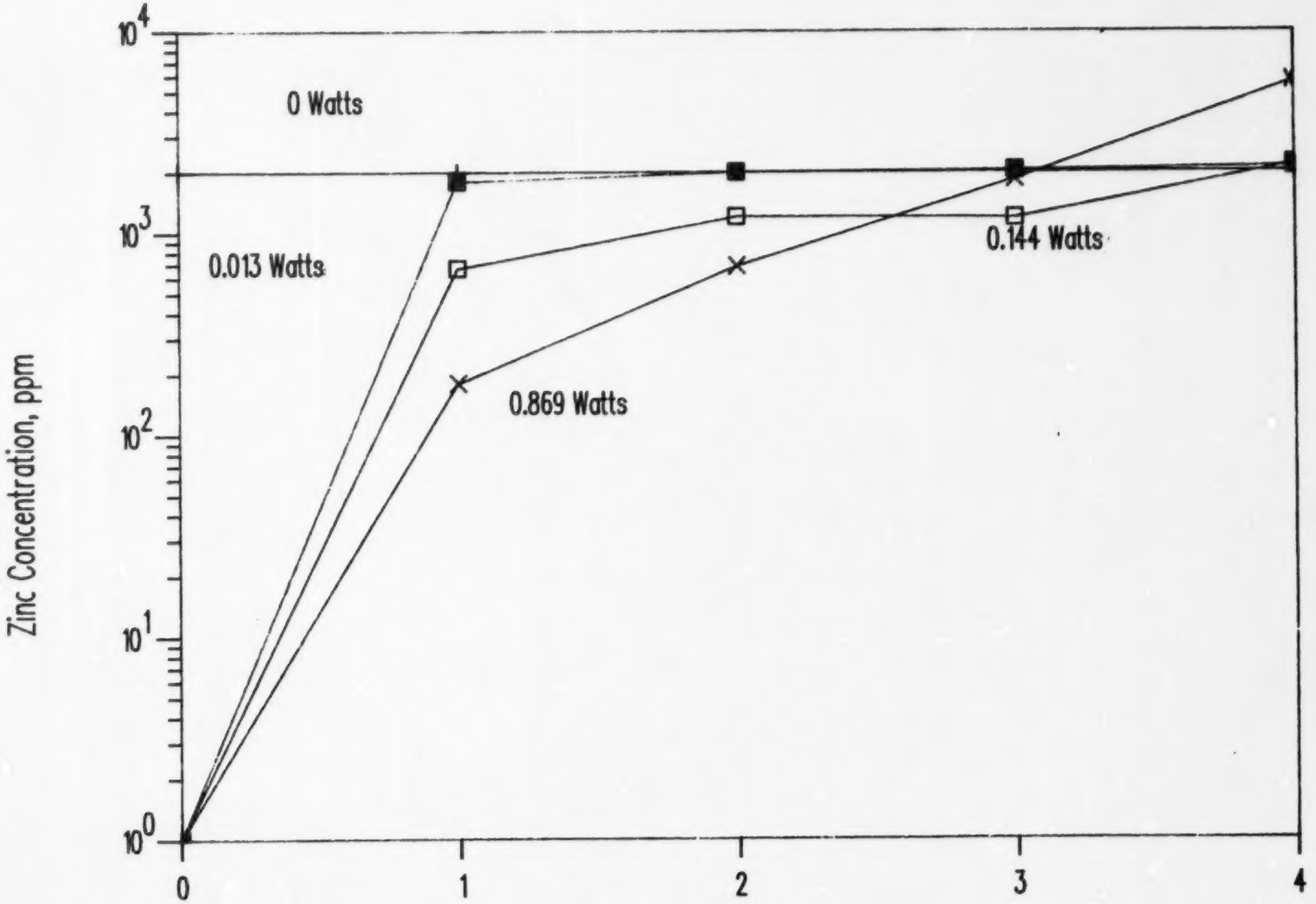


Figure 19. Variation of Zinc Concentration as a Function of Cake Gradient at 0.013, 0.144, and 0.869 W Power Input for 50 Hours' Leaching Time.

ion) of removal was better at a low power that at high power. Figure 20 shows percent zinc removal for 100-hour tests.

Effect of Acoustic Power and Frequency on Zinc Removal

The data from the zinc results was processed to determine the average input power into the soil column. First, the power was determined at the sample points acquired during the test. A typical result is shown in Figure 21. The results are fairly constant up to record number 50. At that point, a slightly lower power is being impressed on the column. This change is due to the need to periodically add more soil to the top chamber as consolidation occurs. The sample powers were averaged to obtain the overall average input power for the test. These are the values that appear in the table of results.

The data from the zinc tests appropriate for the evaluation of the acoustic effect is shown in Table 16. The results from five tests are included along with the parameters that describe the test. Four zinc concentrations are shown for each test. These are the values in the four layers taken from each sample after the test.

The data from the three tests with acoustics, Test 12Z, 14Z, and 15Z, is compared to the control test of 7Z. The results are compared for each layer. Layer 4 is not considered because the method of zinc removal at the cathode had changed between the control, Test 7Z, and the acoustic tests. This allowed a total of 9 removal rates to be calculated, which are attributed to the addition of the acoustic fields.

The most interesting and encouraging results are obtained for Layer 3. For the two cases with frequency of 400 Hz and power levels of 0.44 and 0.86 W, there is an additional removal of 17 percent. Even if the estimate of the concentration of the control was estimated low by 100 mg/kg and the concentration of the acoustic tests were high by 100 mg/kg, the removal would still be 6 percent.

The results from Layer No. 1 are inconclusive. The numbers are all very low and similar. They only differ by a maximum of 50 mg/kg, which is on the order of the accuracy of the analytical methods. Therefore, there is no statistically significant difference.

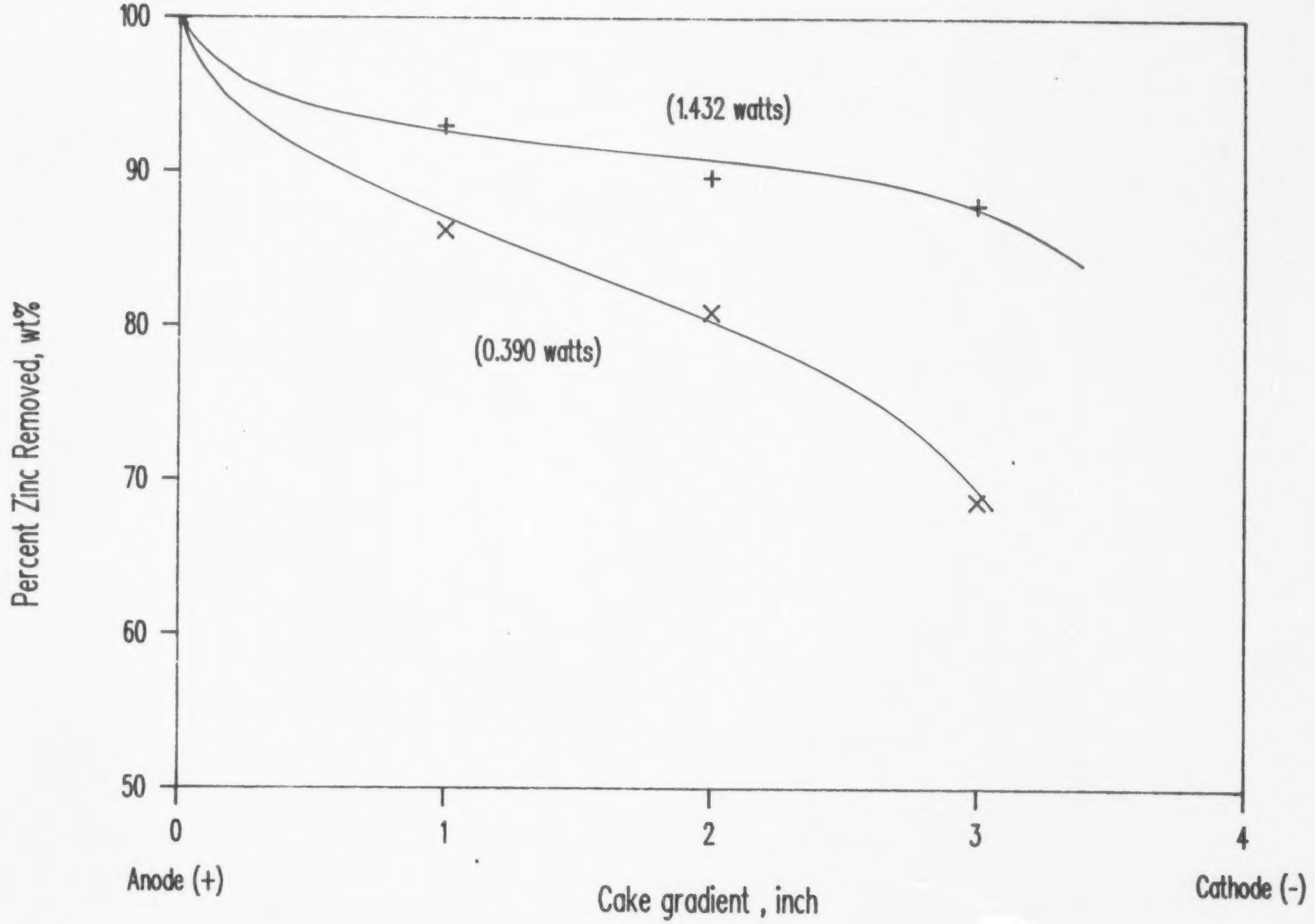


Figure 20. Variation of Zinc Removed (Wt%) as a Function of [illegible]e Gradient at 1.432 W and 0.390 W for 100 Hours' Leaching Time.

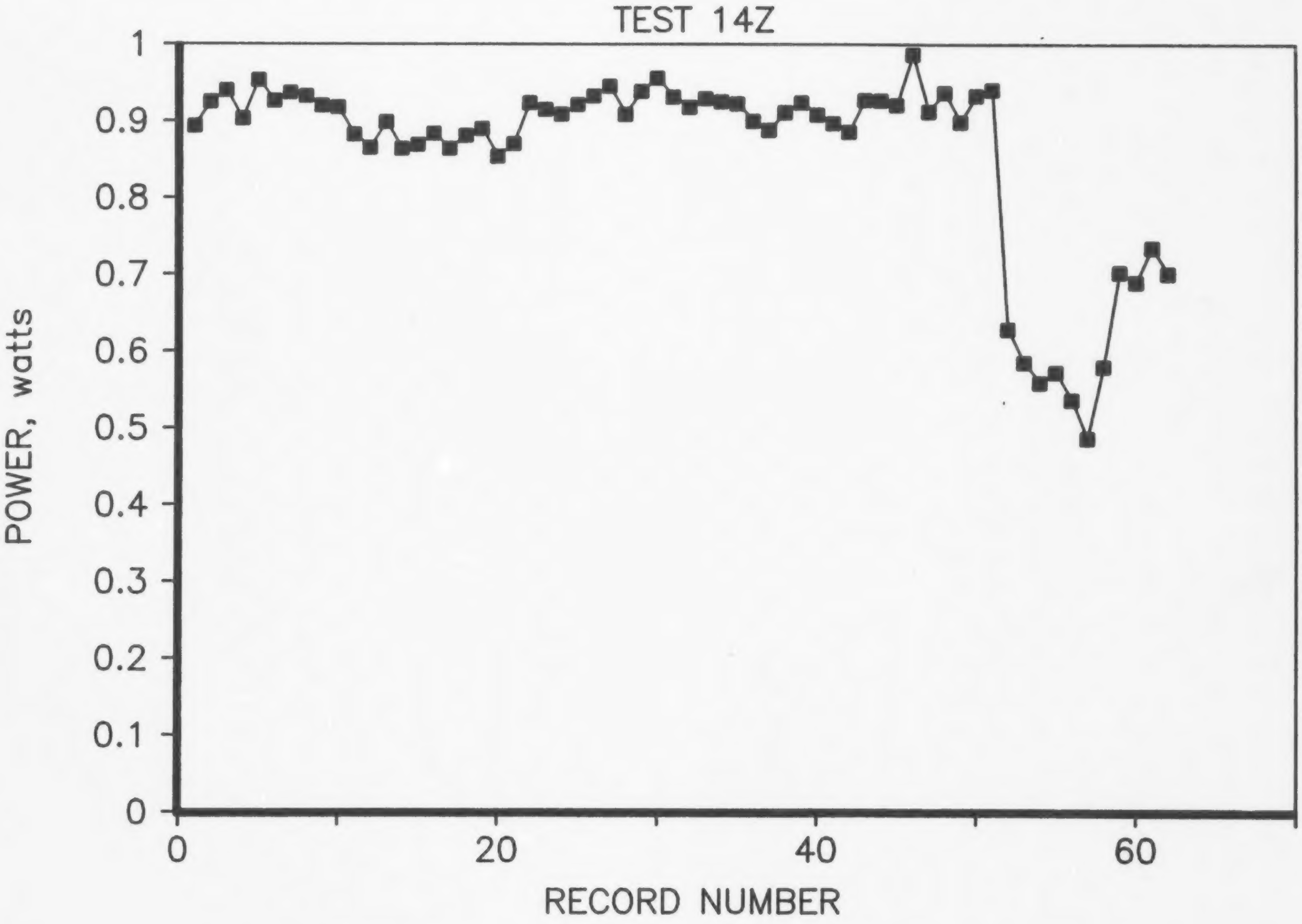


Figure 21. Acoustic Input Power Versus Record Number.

TABLE 16. ACOUSTIC DATA FOR ZINC EXPERIMENTS

Test Number	7Z	12Z	14Z	15Z	13Z
Ave. Electrical power (W)	0.869	0.733	0.730	0.811	0.144
Voltage Field (V/in.)	1.4 - 4.3	1.3 - 4.3	1.1 - 8.17	1.2 - 4.3	0.8 - 2.0
Treatment Time (hours)	50	50	50	50	50
pH Leaching	3.56	3.92	3.36	NA	4.06
pH Leachate	11.65	12.39	10.32	8-11	11.7
Frequency (Hz)	0*	4.00	850	400	0
Power (W)	0*	0.86	0.23	0.44	0
Zinc Concentrations (mg/kg)					
Layer 1	180	205	166	173	671
Layer 2	687	1418	585	644	1206
Layer 3	1847	1524	1858	1532	1185
Layer 4	5644	4479	4513	4054	2185
Additional Removal with Acoustics w.r.t. Test 7Z					
Layer 1	-+-	-14%	8%	4%	NA
Layer 2	---	-200%	15%	6%	NA
Layer 3	---	+17%	0%	17%	NA
Layer 4	---	NA	NA	NA	

* Not applicable.

Layer 2 has mixed results. There is a -200 percent additional removal for Test 12Z with acoustics. This dramatic value is due to the high concentration of zinc in Layer 2. The values for Test 12Z do not smoothly and continuously increase as would be expected. Rather, the values plateau for Layers 2 and 3. A repeat analysis of the sample for Layer 2 was made and it was very close to that reported in the table. It was therefore not a problem with the analysis. The only explanation offered is that the sample was not continuous or homogeneous during the test.

The result for Layer 3, Test 14Z, showed no additional removal. The major differences between this acoustic test and the other acoustic tests were the frequency and power. The power was only 0.23 W compared to 0.44 and 0.86 W for the other tests. The frequency was also twice as high at 850 Hz compared to 400 Hz. Therefore, the lack of removal is probably attributed to the lower power level and higher frequency.

The main observation that can be made regarding the testing is that much more is needed. The analytical results have a high degree of variability. The samples themselves may change over treatment time so that they do not behave as a continuous medium. These factors contribute to the scatter in the results, which makes the accurate determination of the ESD effect difficult. As more and more tests are conducted, the confidence in the results would be improved.

Questions arise as to the importance of the acoustic field even given that there is a demonstrated significant increase in removal. First, over a fixed treatment time, a greater removal may be observed. However, the question is whether there is a lower limit to the remaining concentration that can be removed in the presence of the electric field with or without acoustics. If there is a lower limit, then the application of the acoustics could only shorten time and/or reduce total energy costs. Given this scenario, one would have to trade-off treatment costs (energy and time) versus the capital costs and difficulties to incorporate the acoustic fields.

Other benefits that may be obtained with acoustics is that the treatment zone may be increased; i.e., for a given placement of electrodes for the electric field, the treatment volume may significantly increase. This would certainly represent a greater benefit of the ESD system. This concept has not been tested with the laboratory apparatus used in this project.

Secondary benefits to the acoustics may also exist. For example, acoustics may help to keep permeability of the soil high, because the contaminants concentrate at the removal well. Continuity of the electric field in situ may also improve with the application of the acoustics. Only with further testing, including large-scale field testing, can these questions be answered.

ZINC/CADMIUM TEST

One test was conducted on the zinc/cadmium contaminated soil using the zinc-modified test cell. The objective of the test was to demonstrate that a mixture of ion contaminants in the soil can be transported in the presence of electric field. Results of test are shown in Table 17 and details of the results are provided in Appendix D. The test was conducted at a constant current of 50 mAmp and an average power of 1.913 W for 100 hours. The anode layer was flushed with 0.03N acetic acid solution. Acetic acid was used because it increased the solubility of zinc and cadmium in the soil. Acetic acid forms a zinc acetate complex and a cadmium acetate complex in the presence of zinc and cadmium. These complexes are soluble in water even at a pH higher than 6 (pH 2-9). The formation of these acetate complexes will reduce the formation of hydroxide complexes, which are insoluble in water. The treated cake was divided into five layers. A schematic of the five sections is shown in Figure 22. During zinc tests, the treated cakes were divided into four layers. The last layer (Layer B in contact with cathode) showed an accumulation of the metal species, whereas the first three Layers A, B, and C showed metal removal. To demonstrate that there could be a concentration gradient within the last layer for the zinc/cadmium test, the layer was further subdivided into two fractions.

Results of tests confirm that ESD is effective in moving both zinc and cadmium ions from the cake layer in contact with the anode to the cake layer in contact with the cathode. For example, Layer A shows a removal of 97.05 percent cadmium and 85.09 percent zinc. In Layer C, removal of cadmium

TABLE 17. PERFORMANCE OF ESD PROCESS ON ZINC/CADMIUM SOIL

Cake Gradient	Layer Thickness (In.)	pH	Zinc Concentration (mg/kg) dry soil			Percent Zinc Removed	Cadmium Concentration (mg/kg) dry soil			Percent Cadmium Removed
			Zande	EPA	Ave		Zande	EPA	Ave	
0 Anode (+)	0		0	0	0	100	0	0	0	100
1	1	3.65	167	158	163	85.09	29.2	25	27.1	97.05
2	1	3.55	182	167	175	83.99	26.0	22	24.0	97.39
3	1	3.64	207	197	202	81.52	53.5	51	52.3	94.32
3.5	0.6	4.12	409	344	377	65.51	207	208	207.5	77.45
4 Cathode (-)	0.4	7.66-9.2	7755	7180	7468	-	6187	6310	6249	-

Initial Sample Solids % = 56.73%
Initial Zinc Concentration = 1093 mg/kg dry soil (see Table 7)
Initial Cadmium Concentration = 920 mg/kg dry soil (see Table 7)

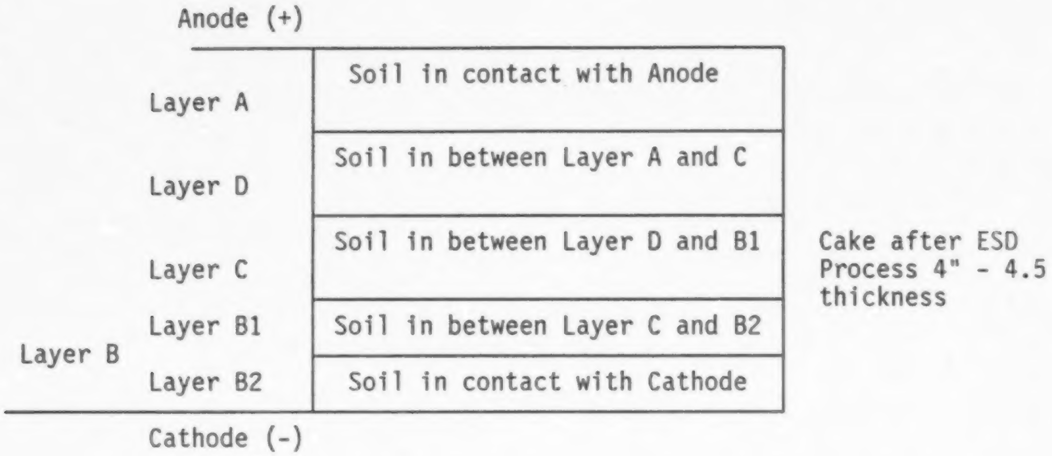

Anode (+)
Layer A
Soil in contact with Anode
Layer D
Soil in between Layer A and C
Layer C
Soil in between Layer D and B1
Cake after ESD Process 4" - 4.5 thickness
Layer B1
Soil in between Layer C and B2
Layer B
Layer B2
Soil in contact with Cathode
Cathode (-)

Figure 22. Schematic of Cake Divided Sections for Zinc/Cadmium Test.

and zinc was 94.32 and 81.52 percent, respectively. Zinc and cadmium were also removed in Layer B1 (the layer which was subdivided). This confirms that there is a concentration gradient in the layer in contact with cathode (B2). This analysis indicates that both zinc and cadmium removal occurred in more than 90 percent of the treated cake.

In the remaining 10 percent of cake (Layer B2, 0.4 in.), there was accumulation of zinc and cadmium due to an increase in pH at the surface of the cathode. The pH of Layer B2 was between 7.7-9.5. Zinc salt is soluble at pH below 6, whereas cadmium salts are soluble at pH below 9. Above pH 9, cadmium would exist as $Cd(OH)_2$, $CdCo_3$, $CdOH+$, $CdOHCl$, which are insoluble in water. Figure 23 shows the solubility of cadmium as a function of pH. The solubility of zinc was discussed earlier in the zinc tests section. Also, for the prepared zinc/cadmium soil, we have calculated the percentage of zinc and cadmium and their forms at different pH values, 7, 8, and 9. Again, as described previously, the calculation was performed using the geochemical computer code MINTEQA2. Table 18 shows calculation for percent distribution of zinc and cadmium at pH values of 7, 8, and 9. More detailed analysis is listed in Appendix E.

Although in the initial concentration of both cadmium and zinc were 0.1 percent, it was observed that there was more cadmium removal than zinc. Hence, it appears that zinc has higher affinity to the soil than does cadmium. According to Benjamin and Leckie(35), zinc will almost completely displace cadmium and compete for the same soil binding sites. Because of the higher binding force of zinc to the soil, more cadmium was removed than zinc.

QUALITY ASSURANCE OF ANALYTICAL DATA: ZINC AND CADMIUM

As part of the quality assurance of analytical procedures, chemical analyses were performed in both U.S. EPA and Zande Laboratories for a set of soil samples. Comparison of analytical data are given in Tables 20 and 21 for zinc and cadmium, respectively. For zinc analysis the variations of data between the two laboratories ranged from 0.48 to 28.91 percent. However, 90 percent of the data showed a variation of less than 20 percent. It was found that the U.S. EPA reported data were generally higher than Zande results. For

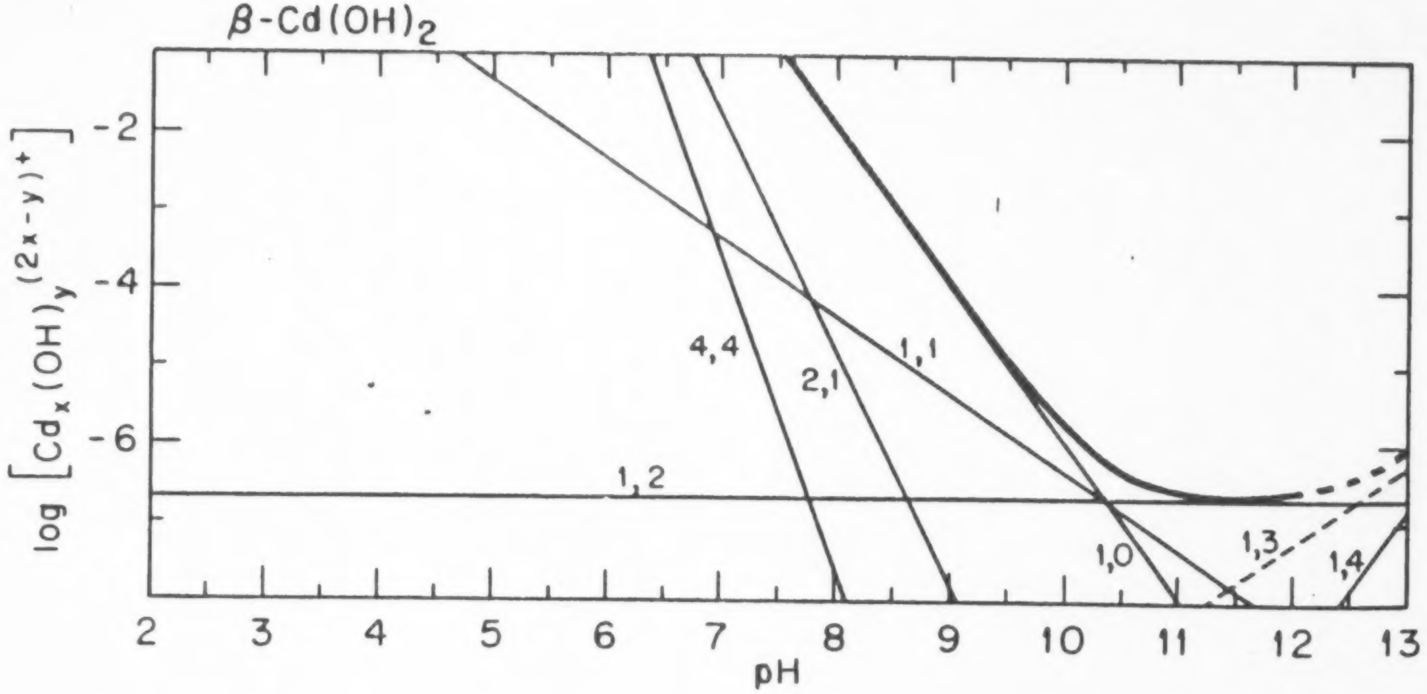


Figure 23. Distribution of Hydrolysis Products (x, y) at I = 1 m and 25° in Solutions Saturated with β-Cd(OH)$_2$. The Heavy Curve is the Total Concentration of Cadmium (II)$^{(34)}$.

TABLE 18. PERCENT IONIC DISTRIBUTION FOR $ZnCl_2$ AND $CdCl_2$ AT PH 7, 8, AND 9

	pH 7	pH 8	pH 9
Zn^{+2}	85.0 Zn^{+2} 4.9 $ZnCl^+$ 8.5 Zn Acetate	74.8 Zn^{+2} 4.3 $ZnCl^+$ 4.5 ZnOH 4.0 $Zn(OH)_2$ 4.1 ZnOHCl AQ	11.9 Zn^{+2} 7.6 ZnOH 70.6 $Zn(OH)_2$ 7.3 ZnOHCl 1.4 Zn Acetate
Cd^{+2}	29.1 Cd^{+2} 53.5 $CdCl^+$ 6.7 $CdCl_2$ 8.2 Cd Acetate 2.0 Cd Acetate 2	28.4 Cd^{+2} 52.6 $CdCl^+$ 6.6 $CdCl_2$ 1.7 CdOHCl 8.3 Cd Acetate 2.1 Cd Acetate 2	22.2 Cd^{+2} 45.5 $CdCl^+$ 6.0 $CdCl_2$ 1.0 $CdOH^+$ 15.1 CdOHCl 7.7 Cd Acetate 2.2 Cd Acetate 2

TABLE 19. ZINC QA DATA

	Zinc Concentration (mg/kg)	
Sample	7/25/89	8/15/89
02363	1167	1195 1164 (duplicate)
02364	1689	1767 1711 (duplicate)
02365	1475	1527 (no duplicate)
02366	1492	1548 1546 (duplicate)
02374	1415	1419 (no duplicate)

TABLE 20. ANALYTICAL DATA FOR ZINC SOIL

Test No.	Zinc Concentration, mg/Kg (DS)		Percent[(a)] Variability Between Zande and U.S. EPA
	Zande	U.S. EPA	
5Z1	2135	1870	6.61
5Z2	383	272	16.95
6Z1	208	210	0.48
6Z2	1878	2220	8.35
7ZA	180	198	4.76
7ZD	687	852	10.72
7ZC	1847	1940	2.46
7ZB	5644	5310	3.05
8ZA	818	852	2.08
8ZD	1542	1900	10.40
8ZC	2066	2100	0.82
8ZB	3214	2720	8.32
9ZA	118.6	155	13.34
9ZD	174.7	253	18.31
9ZC	204.6	371	28.91
9ZB	6341	4820	13.63
10ZA	1175	1800	21.01
10ZD	1529	2000	13.35
10ZC	1501	2040	15.22
10ZB	1722	2120	10.36

(a) Percent variability = $\left| \dfrac{\left(\dfrac{\text{EPA} + \text{Zande}}{2}\right) - \text{EPA}}{\dfrac{\text{EPA} + \text{Zande}}{2}} \right|$

TABLE 21. ANALYTICAL DATA FOR CADMIUM IN SOILS

Sample ID	Cadmium (mg/kg)	
	EPA	Zande
Zn-Cd Feed (1)	866	976
Zn-Cd Feed (2)	873	965
1ZCA	25	292
1ZCB1	208	207
1ZCB2	6310	6167
1ZCC	51	535
1ZCD	22	26

cadmium, however, the analytical data reported from both laboratories agreed fairly well (Table 21). The variation of the results was less than 8.3 percent.

QC Data for Zinc and Cadmium

The QC data provided by U.S. EPA for zinc and cadmium analyses are given in Tables 22 and 23, respectively. When spiked at 1 ppm to the standard solution, recovery of zinc varied from 97 to 106 (see Table 22). Also, the spiking of soil samples with zinc resulted in a recovery of 85 to 103 percent. These spike recovery levels for both liquid and solid samples along with the reported precision data (see duplicate analysis in Table AA) indicate a high precision and accuracy of zinc analysis. Similarly, high precision and accuracy data are reported for cadmium analysis (see Table 23).

INTERNAL AND EXTERNAL QUALITY ASSURANCE AUDITS

Three internal QA audits were performed by Battelle's Quality Assurance Unit which is independent of the research groups that conducted this study. The QA Unit examined the Quality Assurance Project Plan and observed whether the QA/QC requirements are met. The QA Unit also examined the laboratory record books. As a part of the audit program, Zande Laboratory was also audited while they were performing the sample analysis. When deviation from the QAPP was observed, appropriate corrective action was taken and documented.

A Technical System Review (TSR) or the external audit was performed by PEI Associates, Inc. under the direction of U.S. EPA. No concerns were noted in (a) pilot plant operation and sample acquisition and (b) test methods and analytical procedures:

(1) Battelle identified a problem in obtaining a representative sample of the test soil contaminated with decane after treatment. The cake (three inches in diameter and up to 2 inches thick) obtained from the test cell has the consistency of a thick paste. Dewatering was stratified with the drier material on the top. If the sample is mechanically mixed, additional liquid separates, making it difficult to obtain a representative sample. Alternatives were discussed including quartering the cake and taking alternate quarters,

TABLE 22. QC DATA FOR ZINC

Sample ID	Concentration	% Recovery
QC Standard	1 ppm	104
QC Standard	1 ppm	106
5Z2	272 mg/kg	
5Z2 (duplicate)	297 mg/kg	
5Z2 (material spike)		103
5Z2 (material spike, duplicate)		101
QC Standard	1 ppm	97.3
1ZCB1	344 mg/kg	
1ZCB1 (duplicate)	350 mg/kg	
1ZCB1 (material spike)		85
1ZCB1 (material spike, duplicate)		87

TABLE 23. QC DATA FOR CADMIUM

Sample ID	Concentration	% Recovery
QC Standard	1 ppm	90.4
1ZCB1	208 mg/kg	
1ZCB1 (duplicate)	206 mg/kg	
1ZCB1 (material spike)		98
1ZCB1 (material spike, duplicate)		105

extracting the entire cake, or coring the cake with a cork borer. The samples for zinc analysis do not present the same problem because the soil can be dried and ground to a uniform consistency with a mortar and pestle.

(2) There was a calculation error in the standards for the GC analysis. The concentration of the standards were listed as ppm, but these were volume/volume ppm. The analytical data based on these standards were also reported as ppm, but the analytical data should be ppm on a weight/weight basis. The concentration of the standards needed to be converted to nanograms per microliter (using the density of decane), and the analytical data recalculated to obtain a weight/weight relationship.

As a resolution to the first issue, it was decided to quartering the cake (thin slice) and taking alternate quarters for analysis. Extraction of the entire cake or a slice was the preferred approach, but the resources did not permit doing so. As for the second issue, data were recalculated to convert the ppm values from volume/volume basis to weight/weight relationship.

SECTION 6

COMPARISON OF TECHNICAL PERFORMANCE OF ESD WITH OTHER IN SITU TECHNOLOGIES

Based upon the results of this limited study, it is not possible to make a direct quantitative comparison of the ESD technology to other technologies; however, a qualitative comparison is possible. Table 24 summarizes these comparisons.

Organics Treatment

The most likely ESD application for treatment of organics is to enhance the recovery of non-aqueous phase liquids (NAPL) such as solvents and fuel oils. Another possible application is to enhance recovery of more soluble polar organics. This application would be more like the metals treatment. ESD has the potential to reduce NAPL concentrations at or near saturation levels (approximately 5,000 -50,000 mg/kg) to below saturation (approximately 100 - 1,000 mg/kg), but most probably not to low mg/kg or mg/kg levels. This discussion will focus on the potential for increased NAPL recovery.

Pump and Treat

Conventional technology for NAPL recovery consists of some form of groundwater and/or NAPL pumping followed by NAPL separation and/or water treatment. This technology typically can succeed in controlling groundwater and NAPL flow and decreasing the potential for off-site migration. However, success in substantially reducing residual contamination is limited. One limitation of pump-and-treat is that conventional NAPL recovery is dependent upon gravity drainage to bring the NAPL into a recovery well or trench for skimming.

As water tables move up and down and vadose zone moisture levels change, the fraction of the NAPL in this free floating phase changes. As a result, a

TABLE 24. COMPARISON OF ELECTRO-ACOUSTICAL SOIL DECONTAMINATION (ESD) TO OTHER IN-SITU TECHNOLOGIES

Technology	Status	Cost	Limitations
In-Situ Biodegradation	Limited commercial availability	Low-high	Not fully proven, limited to biodegradable compounds.
Inorganics Treatment			
ESD	Bench-scale	Low?	Unproven.
Direct current	Pilot Scale	Low?	Unproven.
Pump and treat	Commercially available	Low initial cost but potentially high life cycle cost.	Never ending, limited to saturate zone.
In-Situ vitrification	Commercially available	High	Stabilizes metals in place, rather than removing them.

TABLE 24. (CONTINUED)

Technology	Status	Cost	Limitations
Organic treatment			
ESD	Early bench scale	Low?	Unproven
Pump and treat	Commercially available	Low initial cost but potentially high life cycle cost.	Never ending, limited to the saturated zone.
Soil venting	Commercially available	Low (without air treatment) Moderate (with air treatment)	Limited to volatiles in the vadose zone.
Heat enhanced soil	Limited commercial availability	Moderate - high	Limited to semivolatiles in the vadose zone.
Steam injection	Limited commercial availability	High	Limited field experience.
RF heating	Pilot scale	Moderate - high	Limited field experience.
Direct current heating	Bench/pilot scale	Moderate - high	Limited field experience
In-Situ vitrification	Commercially available	Highest	Very high temperatures and energy cost.

NAPL recovery system may reduce or even remove the measurable NAPL phase only to have it return under different hydrological conditions.

Under the new RCRA underground tank regulations (CFR 280.64) the minimum remediation requirements are "free product removal." Achievement of this level of remediation may be difficult using conventional pump-and-treat technology. ESD coupled with a conventional pump-and-treat technology has the potential to reduce relatively rapidly the residual NAPL concentrations to levels below those which would result in the free phase NAPL or "free product" layer.

Soil Venting

Soil vent, soil vacuum extraction, and in-site volatilization, is a relatively simple and widely utilized technology for removing volatile organic compounds from the vadose zone. If off-gas treatment is unnecessary, costs are very low; if treatment is required, costs are moderate. Where off- gas treatment is required, ESD has the potential to be less expensive than soil venting and in some cases may prove to be a cost-effective pretreatment prior to soil venting. It is unlikely that ESD can achieve residual concentrations as low as those possible with soil venting for volatiles.

Heat Enhanced Soil Venting

Some vendors of soil venting services have begun to inject heated air to accelerate the process and extend treatment to less volatile or semivolatile organics. The cost of energy to heat the soils is moderately high, dependent of course upon the targeted temperature. Comparisons to ESD are similar to those discussed above for soil venting.

Steam Injection

Injection of steam to treat volatiles and some less-volatile compounds has been demonstrated on a limited number of sites. Sufficient data are not yet available to fully evaluate its feasibility, however energy costs are high. Because of the increased heat capacity of the wet soils, more heat and, therefore, energy are required than for other soil heating technologies.

Radio Frequency Heating

Radio frequency heating is an emerging technology for in situ soil heating. Roy F. Weston, the licensed vendor, intends to couple it with soil venting to achieve accelerated remediation. The comparison to ESD would be very similar to those discussed above.

Direct Current Heating

Direct current is being explored as a means of soil heating. As for all technologies that require increased soil temperature, more energy would be required than for ESD.

In-Situ Vitrification

In-Situ vitrification (ISV) is a commercially available technology in which a direct current is applied to the soils to achieve super heating. This results in soils melting to form a vitrified solid. This differs from direct current heating only in that much higher temperatures are achieved and correspondingly higher energy costs are incurred. ISV is typically applied to inorganics; however, limited data suggest it is applicable to a wide range of organic compounds. The organics are probably either volatilized or are oxidized. Because of the high cost, ISV will most likely only be utilized at very high hazard sites where very low cleanup levels are required. ESD alone would most likely not be applicable to these sites.

Biodegradation

In situ biodegradation is a technology that is receiving widespread attention. It has, to date, been proven effective at a limited number of sites and for a limited number of compounds. The technology is only applicable to biodegradable organics. As the technology evolves, more widespread application may occur. At some sites, ESD may prove to be a cost-effective pretreatment prior to application of an in situ biodegradation technology.

MATERIALS TREATMENT

ESD usage for removal of metal ions is a distinctively different application of the technology from NAPL organics treatment. In this application, ESD may or may not be coupled with a more conventional pump-and-treat technology. ESD has the potential to substantially reduce residual metals concentrations to or below the low mg/kg or mg/kg level. Unlike organics treatment, there are a relatively limited number of technologies for the treatment of metals in-situ.

Direct Current

Direct current has been applied to remove metals in-situ. The Dutch Geokinetics process is a promising technology, utilizing a novel circulating fluid electrode to prevent metals deposition. The direct-current technology is a part of the ESD technology; however, by combining electrical and acoustical fields, ESD has the potential to improve treatment efficiency.

Pump and Treat

As discussed for organics treatment, the pump-and-treat technology is potentially successful at hydraulically controlling a plume of contaminated groundwater but is frequently ineffective at substantially reducing residual soil contamination. ESD has the potential to improve substantially this treatment.

In-Situ Vitrification

In-situ vitrification was designed for and is typically applied to inorganic contaminants. Direct current is applied to heat the soil to its melting point and vitrify the contaminated soil into an impermeable mass. This technology does not remove the metals but rather immobilizes them in situ. The technology requires substantially more energy and funds than does ESD.

SECTION 7

CONCLUSIONS

(1) Electro-acoustic decontamination of soil in a laboratory mode was proven technically feasible for inorganic contaminants.

(2) Zinc removal/concentration (80-90 percent) was observed in the presence of the electric field.

(3) There appears to be a combined electric and acoustics effect during zinc removal. However, further testing is required to determine accurately the magnitude of the effect.

(4) Longer leaching times yielded higher zinc removal efficiencies.

(5) Higher power levels yielded higher zinc removal rates.

(6) Cadmium/zinc removal/concentration (90-95 percent) was observed in the presence of the electric field.

(7) A large discrepancy was observed between U.S. EPA and Zande Labs decane analyses.

(8) Since a large variability in analytical determination of decane in the soil was observed, no definitive conclusions can be drawn on the effect of electro-acoustics on decane removal from soils.

SECTION 8

RECOMMENDATIONS

Based on Phase 1 laboratory experimental results for decontamination of heavy metals in clayed soil, a study is recommended and should be conducted to further evaluate the ESD process in field conditions. Such a study would validate the Phase I results and would provide the basis for developing design and operational changes for successful field applications.

We also recommend no additional work on the decane contaminated soil until the analytical and experimental problem can be solved. The results from the decane experiments were inconclusive because of substantial experimental uncertainty in the decane analysis and also possibly in experimental procedures.

SECTION 9

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APPENDIX A

DECANE DATA

DECANE TEST DATA

Initial Decane % as dosed in the lab = 8.0 (D.B.)
Initial Decane % as dosed in the lab = 4.21 (W.B.)
Initial Solids % as dosed in the lab = 52.68

Test #	Test Time Hr	Voltage volts/in.	Current Amp	Acoustic Power Watts	Final Cake Solids %	ESD Treated Soil Analysis				Comments
						EPA Decane		Zande Decane		
						%(W.B.)	%(D.B.)	%(W.B.)	%(D.B.)	
10D*	1.25	37.5	0.18	0	68.52$^{(a)}$	0.800	1.17	3.7395	5.457	No Flushing, sample was mixed for analysis.
11D*	1.25	25.0	0.16	0	66.94$^{(a)}$	2.83	4.23	3.7423	5.59	No Flushing, sample was mixed for analysis.
12D*	1.25	12.5	0.08	0	60.62$^{(a)}$	1.680	2.77	3.1185	5.144	No Flushing, sample was mixed for analysis.
13D*	1.75	25.0	0.19	0	66.41$^{(a)}$	3.180	4.79	3.3757	5.08	Flushing was performed. It seems that the osmotic dewatering rate is higher than the soil absorbtion rate, so some of the flushing water leaked from the side due to shrinkage of soil. Sample was mixed for analysis.

DECANE TEST DATA
(Continued)

Initial Decane % as dosed in the lab = 7.97 (D.B.)
Initial Decane % as dosed in the lab = 4.20 (W.B.)
Initial Solids % as dosed in the lab = 52.68

Test #	Test Time Hr	Voltage volts/in.	Current Amp	Acoustic Power Watts	Final Cake Solids %	ESD Treated Soil Analysis				Comments
						EPA Decane		Zande Decane		
						%(W.B.)	%(D.B.)	%(W.B.)	%(D.B.)	
14D*	1.25	25.0	0.15	0	66.30(a)	3.170	4.78	3.7358	5.63	This test is a repeat of Test #11D. No flushing. Sample was mixed for analysis.
15D*	1.25	0	0	0	53.73(a)	3.480	6.476	3.4169	6.359	Control. No electric. No flushing. No acoustic. Sample was mixed for analysis.
17D*	2.0	12.5	0.08	0.697	64.8(a)	3.0900	4.77	3.320	5.12	
19D*	141.5	6.25-41.25	0.008	0	64.7(a)	3.1900	4.93	3.7500	5.80	This test was done in specially designed graduate cylinder for flushing purposes. Sample was mixed for analysis.
20D*	24.0	5.0	0.009	0	64.5(a)	3.2100	4.98	3.5700	5.53	Sample was mixed for analysis.
21D*	24.0	5.0	0.017	0.697	60.7(a)	3.400	5.60	3.700	6.10	Sample was mixed for analysis.

DECANE TEST DATA
(Continued)

Initial Decane % as dosed in the lab = 7.97 (D.B.)
Initial Decane % as dosed in the lab = 4.20 (W.B.)
Initial Solids % as dosed in the lab = 52.68

Test #	Test Time Hr	Voltage volts/in.	Current Amp	Acoustic Power Watts	Final Cake Solids %	ESD Treated Soil Analysis EPA Decane %(W.B.)	ESD Treated Soil Analysis EPA Decane %(D.B.)	ESD Treated Soil Analysis Zande Decane %(W.B.)	ESD Treated Soil Analysis Zande Decane %(D.B.)	Comments
22D*	1.25	0	0	1 watt 400 Hz	54.7[(a)]	2.890	5.28	3.6900	6.75	Sample was mixed for analysis.
23D*	1.25	0	0	0.47 watts 400 Hz	55.3[(a)]	3.4400	6.22	3.6400	6.58	Sample was mixed for analysis.
26DA*	2.0	37.5	0.13	0	73.67[(a)]	3.96	5.38	6.71	9.11	Cake was divided into three sections. Section A - closer to the anode. Section B - between Section A & C. Each section is 0.5 in thickness. Total cake thickness 2.5 in. No mixing.
26DA1*	2.0	37.5		0	73.67[(a)]	3.90	5.29	6.55	8.89	
26DA2*	2.0	37.5		0	73.67[(a)]	4.45	6.040	5.82	7.91	
26DB*	2.0	37.5		0	70.84[(a)]	4.3	6.07	5.95	8.40	

DECANE TEST DATA
(Continued)

Initial Decane % as dosed in the lab = 7.97 (D.B.)
Initial Decane % as dosed in the lab = 4.20 (W.B.)
Initial Solids % as dosed in the lab = 52.68

Test #	Test Time Hr	Voltage volts/in.	Current Amp	Acoustic Power Watts	Final Cake Solids %	ESD Treated Soil Analysis				Comments
						EPA Decane		Zande Decane		
						%(W.B.)	%(D.B.)	%(W.B.)	%(D.B.)	
26DC*	2.0	37.5		0	61.97(a)	3.9	6.29	5.53	8.9	
27DA*	2.0	45.0	0.11	0	72.65(a)	4.35	5.987	6.47	8.91	Cake was divided into three sections. Section A - closer to the anode. Section B - between Section A & C. Each section is 0.5 in thickness. Total cake thickness 2.5 in.
27DB*	2.0	45.0		0	61.24(a)	4.17	6.809	5.21	8.51	
27DC*	2.0	45.0		0	50.58(a)	3.56	7.038	5.89	11.64	
28DA*	2.0	25.0	0.10	0	70.35(a)	4.29	6.098	5.93 7.25	9.37	Cake was divided into three sections. Section A - closer to the anode. Section B - between Section A & C. Each section is 0.5 in thickness. Total cake thickness 2.5 in.

DECANE TEST DATA
(Continued)

Initial Decane % as dosed in the lab = 7.97 (D.B.)
Initial Decane % as dosed in the lab = 4.20 (W.B.)
Initial Solids % as dosed in the lab = 52.68

Test #	Test Time Hr	Voltage volts/in.	Current Amp	Acoustic Power Watts	Final Cake Solids %	ESD Treated Soil Analysis				Comments
						EPA Decane		Zande Decane		
						%(W.B.)	%(D.B.)	%(W.B.)	%(D.B.)	
28DB*	2.0	25.0		0	65.60(a)	4.07	6.204	4.98	7.6	
28DC*	2.0	25.0		0	59.89(a)	3.34	5.576	6.28	10.49	
30DA*	2.0	37.5	0.11	0.697 400 Hz	73.79(a)	4.44	6.017	6.10	8.27	Cake was divided into three sections. Section A - closer to the anode. Section B - between Section A & C. Each section is 0.5 in thickness. Total cake thickness 2.5 in.
30DB*	2.0	37.5		0.697 400 Hz	68.01(a)	3.90	5.13	5.94	8.73	
30DC*	2.0	37.5		0.697 400 Hz	61.40(a)	3.54	5.77	5.13	8.36	

(a) Final solids percent reported by Zande.

* Note: 2 in. cake was used in test 10D through 23D.
2 1/2 in cake was used in 26D through 30D.

APPENDIX B

ZINC DATA

ZINC TEST DATA

Test #	Distance Between Electrodes In.	Test Time Hr.	Voltage V/in.	Average Electrical Power watts	Average Acoustic Power watts	Acoustic Frequency HZ	Initial Cake weight gm	Final Cake weight gm	weight leachate collected gm	Final Solids Percent %	Initial Zinc Conc. mg/kg (DB)	Analytical Lab. Analysis: Ianode Zinc Analysis mg/kg (DB)	Analytical Lab. Analysis: EPA Zinc Analysis mg/kg (DB)	(a) Percent Zinc Removal %	(b) Anode Flushing Solution PH	(c) Leachate PH	Comment
3E	2.0	1.25	10	5.780	0	0	352.3	317.2	35.1	65.04	1685	1697	2150	-0.7	----	---	The Whole Cake was Mixed and sent for analysis
4E	2.0	1.25	20	24.120	0	0	351.1	286.7	64.4	71.15	1685	1368	2050	18.81	----	----	The Whole Cake was Mixed and sent for analysis
*5E1	8.0	191.3	2.5--12.5	0.450	0	0	313.0	277	292.5	67.71	1685	2110 2160 (R)	1870	-26.94 (a)	----	----	cake close to cathode (1/2 cake)
*5E2	8.0	191.3	2.5--12.5	0.450	0	0	313.0	277	292.5	65.81	1685	384 381 (R)	272	77.3	----	----	cake close to anode (1/2 cake)
*6E1	8.0	191.3	2.5--12.5	0.450	0	0	313.2	-----	------	------	1685	213 203 (R)	210	87.36	----	----	cake close to anode (1/2 cake)
*6E2	8.0	191.3	2.5--12.5	0.450	0	0	313.2	-----	------	------	1685	1822 1934 (R)	2220	-11.45 (a)	----	----	cake close to cathode (1/2 cake)
7EA	4.5	50	1.4--4.3	0.869	0	0	839.5	180.1	------	59.85	1685	180.4	190	89.29	3.56	11.65	cake in contact with anode
7ED	4.5	50	1.4--4.3	0.869	0	0	839.5	140.0	------	62.06	1685	687.1	852	59.22	3.56	11.65	cake in contact with anode layer
7EC	4.5	50	1.4--4.3	0.869	0	0	839.5	165	------	66.6	1685	1846.0	1940	-9.6 (a)	3.56	11.65	cake in contact with cathode layer
7EB	4.5	50	1.4--4.3	0.869	0	0	839.5	120.9	------	65.70	1685	5644.3	5310	-234.97 (a)	3.56	11.65	cake in contact with cathode
8EA	4.5	25	1.3--5.3	0.500	0	0	840.5	179.1	132.1	59.63	1685	818	852	51.45	3.02	11.00	cake in contact with anode
8ED	4.5	25	1.3--5.3	0.500	0	0	840.5	182.8	132.1	64.19	1685	1542	1900	8.49	3.02	11.00	cake in contact with anode layer
8EC	4.5	25	1.3--5.3	0.500	0	0	840.5	164.3	132.1	66.89	1685	2066	2100	-22.61 (a)	3.02	11.00	cake in contact with cathode layer
8EB	4.5	25	1.3--5.3	0.500	0	0	840.5	180.2	132.1	60.7	1685	3214	2720	-90.74 (a)	3.02	11.00	cake in contact with cathode
9EA	4.5	100	0.3--20	1.423	0	0	839	176.1	644	61.27	1685	118.6	155	92.96	3.37	11.25	cake in contact with anode
9ED	4.5	100	0.3--20	1.423	0	0	839	178	644	72.38	1685	174.7	253	89.63	3.37	11.25	cake in contact with anode layer
9EC	4.5	100	0.3--20	1.423	0	0	839	182.3	644	65.06	1685	204.8	371	87.86	3.37	11.25	cake in contact with cathode layer
9EB	4.5	100	0.3--20	1.423	0	0	839	193.5	644	57	1685	6341	4820	-276.3 (a)	3.37	11.25	cake in contact with cathode

ZINC TEST DATA

Test No.	Distance Between Electrodes in.	Test Time Hr.	Voltage V/in.	Average Electrical Power watts	Average Acoustic Power watts	Acoustic Frequency HZ	Initial Cake weight gms	Final Cake weight gms	weight leachate collected gms	Final Solids Percent %	Initial Zinc Conc. mg/kg (DB)	Analytical Lab. Analysis: Inade Zinc Analysis mg/kg (DB)	Analytical Lab. Analysis: EPA Zinc Analysis mg/kg (DB)	(a) Percent Zinc Removal %	(b) Anode Flushing Solution PH	(c) Leachate PH	Comment
102A	4.5	50	0.36--0.46	0.013	1.302	400	841	193.6	40	57.48	1685	1167 1195(R) 1164(R)	1800	30.25	------	------	cake in contact with anode
102B	4.5	50	0.36--0.46	0.013	1.302	400	841	179.5	40	60.22	1685	1492 1540(R) 1546(R)	2000	9.20	------	------	cake in contact with anode layer
102C	4.5	50	0.36--0.46	0.013	1.302	400	841	170.2	40	61.38	1685	1475 1527(R)	2040	10.92	------	------	cake in contact with cathode layer
102D	4.5	50	0.36--0.46	0.013	1.302	400	841	180.6	40	62.53	1685	1689 1767(R) 1711(R)	2120	-2.22 (a)	------	------	cake in contact with cathode
112A	4.5	25	1.3--4.0	0.517	0.81	400	841.6	170.02	----	61.16	1685	622	-----	63.09	------	------	cake in contact with anode
112B	4.5	25	1.3--4.0	0.517	0.81	400	841.6	208.42	----	65.87	1685	1772 1445(R)	-----	4.54	------	------	cake in contact with anode layer
112C	4.5	25	1.3--4.0	0.517	0.81	400	841.6	129.7	----	60.1	1685	1357 1505(R)	-----	12.7	------	------	cake in contact with cathode layer
112D	4.5	25	1.3--4.0	0.517	0.81	400	841.6	165.12	----	66.52	1685	2965	-----	-75.96 (a)	------	------	cake in contact with cathode
122A	4.5	50	1.3--4.3	0.733	0.86	400	841	150	111.5	59.43	1685	205	-----	87.83	3.92	12.39	cake in contact with anode
122B	4.5	50	1.3--4.3	0.733	0.86	400	841	154.9	111.5	63.18	1685	1418 1419(R)	-----	15.82	3.92	12.39	cake in contact with anode layer
122C	4.5	50	1.3--4.3	0.733	0.86	400	841	120.4	111.5	65.71	1685	1524	-----	9.56	3.92	12.39	cake in contact with cathode layer
122D	4.5	50	1.3--4.3	0.733	0.86	400	841	120.0	111.5	66.33	1685	4479	-----	-165.8 (a)	3.92	12.39	cake in contact with cathode
132A	4.5	50	0.8--2.0	0.144	0	0	839.3	190.9	94.5	58.12	1685	671	-----	60.18	4.06	11.7	cake in contact with anode
132B	4.5	50	0.8--2.0	0.144	0	0	839.3	164	94.5	60.88	1685	1288	-----	28.43	4.06	11.7	cake in contact with anode layer
132C	4.5	50	0.8--2.0	0.144	0	0	839.3	164.9	94.5	63.14	1685	1185	-----	29.67	4.06	11.7	cake in contact with cathode layer
132D	4.5	50	0.8--2.0	0.144	0	0	839.3	219.3	94.5	64.65	1685	2185	-----	-29.67 (a)	4.06	11.7	cake in contact with cathode

ZINC TEST DATA

Test #	Distance Between Electrodes in	Test Time Hr	Voltage V/in	Average Electrical Power watts	Average Acoustic Power watts	Acoustic Frequency HZ	Initial Cake weight gms	Final Cake weight gms	weight leachate collected gms	Final Solids Percent %	Initial Zinc Conc. mg/kg (DB)	Analytical Lab. Analysis		(z) Percent Zinc Removal %	(b) Anode Flushing Solution PH	(c) Leachate PH	Comment
												Zone Zinc Analysis mg/kg (DB)	EPA Zinc Analysis mg/kg (DB)				
142A	4.5	50	1.1--0.17	0.730	0.233	850	840.7	170.1	204.1	59.32	1685	166	-----	90.15	3.36	10.32	cake in contact with anode
142B	4.5	50	1.1--0.17	0.730	0.233	850	840.7	154.5	204.1	62.8	1685	585	-----	65.28	3.36	10.32	cake in contact with anode layer
142C	4.5	50	1.1--0.17	0.730	0.233	850	840.7	182.5	204.1	64.23	1685	1858	-----	-10.27 (a)	3.36	10.32	cake in contact with cathode layer
142D	4.5	50	1.1--0.17	0.730	0.233	850	840.7	194.8	204.1	65.27	1685	4513	-----	-167.8 (a)	3.36	10.32	cake in contact with cathode
152A	4.5	50	1.2--4.3	0.011	0.44	400	839.6	181.6	1550.3 #	59.64	1685	173	-----	89.73	----	8--11	cake in contact with anode *
152B	4.5	50	1.2--4.3	0.011	0.44	400	839.6	188.6	1550.3 #	62.14	1685	644	-----	61.78	----	8--11	cake in contact with anode layer
152C	4.5	50	1.2--4.3	0.011	0.44	400	839.6	166.3	1550.3 #	64.7	1685	1532	-----	9.08	----	8--11	cake in contact with cathode layer
152D	4.5	50	1.2--4.3	0.011	0.44	400	839.6	196.8	1550.3 #	65.24	1685	4059	-----	-140.9	----	8--11	cake in contact with cathode
162A	4.5	100	1.3--2.4	0.390	1.003	412	840	192.1	8437	59.6	1685	232.5	-----	86.2	3.74	4.0	cake in contact with anode
162B	4.5	100	1.3--2.4	0.390	1.003	412	840	200.9	8437	61.42	1685	322.3	-----	80.87	3.74	4.0	cake in contact with anode layer
162C	4.5	100	1.3--2.4	0.390	1.003	412	840	202.1	8437	62.39	1685	528.6	-----	68.63	3.74	4.0	cake in contact with cathode layer
162D	4.5	100	1.3--2.4	0.390	1.003	412	840	185.2	8437	64.69	1685	5505 4991(D)	-----	-211.5	3.74	4.0	cake in contact with cathode

(a): Percent Zinc Accumulated

#: Test was performed in a graduated cylinder designed for flushing purposes

(b): PH of flushing water solution at the end of test

(c): PH of leachate at the end of test

(D): Duplicate analysis

(z): Percent Zinc Removed Based on Zone Analytical Data

*: Flushing water drained through crack in the soil

APPENDIX C

GEOCHEMICAL CALCULATIONS FOR ZINC SOIL

```
1
   PC  VERSION: MINTEQA2   DATE OF CALCULATIONS: 08/24/89     TIME: 16:38:42

                    Zinc Solubility and Percent Distribution at pH 6

--------------------------------------------------------------------------------
--
  Temperature (Celsius):  25.00
  Units of concentration: PPM
  Ionic strength to be computed.
  Carbonate concentration represents carbonate alkalinity.
  Do not automatically terminate if charge imbalance exceeds 30%
  Precipitation is allowed only for those solids specified as ALLOWED
    in the input file (if any).
  The maximum number of iterations is: 100
  The method used to compute activity coefficients is: Debye-Huckel equation
  Do not print the full species database including gram-formula weights and
    Debye-Huckel parameters.


--------------------------------------------------------------------------------
-

     950  0.200E+04   -1.82
     180  0.200E+04   -1.25
     330  0.101E-04   -6.00
0 H2O HAS BEEN INSERTED AS A COMPONENT
   3  1
     330      6.0000     0.0000
0INPUT DATA BEFORE TYPE MODIFICATIONS
0    ID         NAME        ACTIVITY GUESS     LOG GUESS    ANAL TOTAL
     950  Zn+2                   1.514E-02        -1.820   2.000E+03
     180  Cl-1                   5.623E-02        -1.250   2.000E+03
     330  H+1                    1.000E-06        -6.000   1.008E-05
       2  H2O                    1.000E+00         0.000   0.000E+00
0    ID         NAME        ANAL MOL    CALC MOL    ACTIVITY    LOG ACTVTY       GAMMA
    NEW LOGK    DIFF FXN
     950  Zn+2             2.000E+03  0.000E+00 1.514E-02    -1.82000     1.000000
    0.0000   0.000E+00
     180  Cl-1             2.000E+03  0.000E+00 5.623E-02    -1.25000     1.000000
    0.0000   0.000E+00
     330  H+1              1.008E-05  0.000E+00 1.000E-06    -6.00000     1.000000
    6.0000   0.000E+00
       2  H2O              0.000E+00  0.000E+00 1.000E+00     0.00000     1.000000
    0.0000   0.000E+00
0
     CHARGE BALANCE: UNSPECIATED
0           SUM OF CATIONS= 6.144E-02 SUM OF ANIONS = 5.664E-02
0           PERCENT DIFFERENCE =  4.062E+00   (ANIONS - CATIONS)/(ANIONS +
CATIONS)
1
```

Zinc at μH 6 (pg 2)

```
0    SPECIES:   TYPE  III - FIXED SOLIDS
0   ID         NAME          CALC MOL         LOG MOL       NEW LOGK       DH
       2  H2O              -3.352E-05       -4.475       0.001       0.000
     330  H+1               3.353E-05       -4.475       6.000       0.000
1

   PC  VERSION: MINTEQA2   DATE OF CALCULATIONS: 08/24/89     TIME: 16:39:12


  PERCENTAGE DISTRIBUTION OF COMPONENTS AMONG          dissolved and adsorbed
species


+Zn+2
+                    94.0      PERCENT BOUND IN SPECIES #     950   Zn+2

+                     5.7      PERCENT BOUND IN SPECIES #9501800   ZnCl +

+Cl-1
+                    96.7      PERCENT BOUND IN SPECIES #     180   Cl-1

+                     3.1      PERCENT BOUND IN SPECIES #9501800   ZnCl +

+H2O
+                    48.9      PERCENT BOUND IN SPECIES #9501804   ZnOHCl AQ

+                    50.1      PERCENT BOUND IN SPECIES #9503300   ZnOH +

+H+1
+                    48.9      PERCENT BOUND IN SPECIES #9501804   ZnOHCl AQ

+                    50.1      PERCENT BOUND IN SPECIES #9503300   ZnOH +



                  -------------------------------------------------------
                  ----------- EQUILIBRATED MASS DISTRIBUTION -----------
0
 IDX     NAME           DISSOLVED             SORBED              PRECIPITATED
                    MOL/KG    PERCENT     MOL/KG    PERCENT     MOL/KG    PERCENT

 950  Zn+2        3.072E-02   100.0    0.000E+00     0.0    0.000E+00     0.0
 180  Cl-1        5.664E-02   100.0    0.000E+00     0.0    0.000E+00     0.0
   2  H2O         3.352E-05   100.0    0.000E+00     0.0    0.000E+00     0.0
 330  H+1        -3.352E-05   100.0    0.000E+00     0.0    0.000E+00     0.0
0
   CHARGE BALANCE: SPECIATED
0         SUM OF CATIONS =  5.951E-02 SUM OF ANIONS   5.475E-02
```

Zinc at pH 6 (pg 3)

```
0         PERCENT DIFFERENCE =   4.168E+00   (ANIONS - CATIONS)/(ANIONS +
CATIONS)
0      NONCARBONATE ALKALINITY =   1.298E-08
0 IONIC STRENGTH = :  8.601E-02
1

   PC  VERSION: MINTEQA2   DATE OF CALCULATIONS: 08/24/89     TIME: 16:39:13

0Saturation indices and stoichiometry of all minerals
0     ID #      NAME       Sat. Index          Stoichiometry (in parentheses) of
each component
   4195000 ZNCL2            -11.702     (  1.000)950   (  2.000)180
   2095000 ZN(OH)2 (A)       -2.370     ( -2.000)330   (  1.000)950   (  2.000)  2
   2095001 ZN(OH)2 (C)       -2.120     ( -2.000)330   (  1.000)950   (  2.000)  2
   2095002 ZN(OH)2 (B)       -1.670     ( -2.000)330   (  1.000)950   (  2.000)  2
   2095003 ZN(OH)2 (G)       -1.630     ( -2.000)330   (  1.000)950   (  2.000)  2
   2095004 ZN(OH)2 (E)       -1.420     ( -2.000)330   (  1.000)950   (  2.000)  2
   4195001 ZN2(OH)3CL        -2.417     ( -3.000)330   (  2.000)950   (  3.000)  2  (
1.000)180
   4195002 ZN5(OH)8CL2       -2.854     ( -8.000)330   (  5.000)950   (  8.000)  2  (
2.000)180
   2095005 ZNO(ACTIVE)       -1.230     ( -2.000)330   (  1.000)950   (  1.000)  2
   2095006 ZINCITE           -1.060     ( -2.000)330   (  1.000)950   (  1.000)  2
```

```
1
   PC  VERSION: MINTEQA2   DATE OF CALCULATIONS: 08/24/89     TIME: 16:48:04

                  Zinc Solubility and Percent Distribution at pH 9.7

--------------------------------------------------------------------------------
--
  Temperature (Celsius):  25.00
  Units of concentration: PPM
  Ionic strength to be computed.
  Carbonate concentration represents carbonate alkalinity.
  Do not automatically terminate if charge imbalance exceeds 30%
  Precipitation is allowed only for those solids specified as ALLOWED
    in the input file (if any).
  The maximum number of iterations is: 100
  The method used to compute activity coefficients is: Debye-Huckel equation
  Do not print the full species database including gram-formula weights and
    Debye-Huckel parameters.

--------------------------------------------------------------------------------
-

Zn→ 950  0.200E+04   -1.82
Cl→ 180  0.218E+04   -1.25
Na→ 500  0.100E+03   -2.40
    330  0.101E-04   -9.70
O H2O HAS BEEN INSERTED AS A COMPONENT
   1   1
    330     9.7000     0.0000
OINPUT DATA BEFORE TYPE MODIFICATIONS
O   ID        NAME       ACTIVITY GUESS    LOG GUESS   ANAL TOTAL
     950  Zn+2                1.514E-02       -1.820   2.000E+03
     180  Cl-1                5.623E-02       -1.250   2.181E+03
     500  Na+1                3.981E-03       -2.400   1.000E+02
     330  H+1                 1.995E-10       -9.700   1.008E-05
       2  H2O   -             1.000E+00        0.000   0.000E+00
O   ID        NAME       ANAL MOL    CALC MOL    ACTIVITY    LOG ACTVTY     GAMMA
   NEW LOGK     DIFF FXN
     950  Zn+2          2.000E+03  0.000E+00 1.514E-02    -1.82000    1.000000
    0.0000    0.000E+00
     180  Cl-1          2.181E+03  0.000E+00 5.623E-02    -1.25000    1.000000
    0.0000    0.000E+00
     500  Na+1          1.000E+02  0.000E+00 3.981E-03    -2.40000    1.000000
    0.0000    0.000E+00
     330  H+1           1.008E-05  0.000E+00 1.995E-10    -9.70000    1.000000
    9.7000    0.000E+00
       2  H2O           0.000E+00  0.000E+00 1.000E+00     0.00000    1.000000
    0.0000    0.000E+00
O
     CHARGE BALANCE: UNSPECIATED
```

Zinc at pH 9.7 (pg 2)

```
 9501802  ZnC13 -          1.143E-10  0.0000000   -10.04407     0.790735
0.602      9.560
 9501803  ZnC14 -2         5.251E-12  0.0000000   -11.66251     0.414223
0.582     10.960
 9503300  ZnOH +           2.986E-05  0.0000237    -4.62477     0.794654
-8.860     13.399
 9503301  Zn(OH)2 AQ       2.269E-02  0.0230788    -1.63679     1.017006
-16.906       0.000
 9503302  Zn(OH)3 -        7.763E-03  0.0061687    -2.20980     0.794654
-28.299       0.000
 9503303  Zn(OH)4 -2       2.072E-04  0.0000826    -4.08282     0.398760
-40.800       0.000

0    SPECIES:   TYPE  III - FIXED SOLIDS
0   ID            NAME      CALC MOL        LOG MOL       NEW LOGK       DH
       2  H2O              -7.065E-02       -1.151        0.001        0.000

1
   PC  VERSION: MINTEQA2   DATE OF CALCULATIONS: 08/24/89     TIME: 16:48:38


  PERCENTAGE DISTRIBUTION OF COMPONENTS AMONG          dissolved and adsorbed
species


+Zn+2
+                  73.9    PERCENT BOUND IN SPECIES #9503301   Zn(OH)2 AQ

+                  25.3    PERCENT BOUND IN SPECIES #9503302   Zn(OH)3 -


+Cl-1
+                  99.9    PERCENT BOUND IN SPECIES #    180   Cl-1


+Na+1
+                 100.0    PERCENT BOUND IN SPECIES #    500   Na+1


+H+1
+                 855.1    PERCENT BOUND IN SPECIES #9501804   ZnOHCl AQ
+                >1000.    PERCENT BOUND IN SPECIES #3300020   OH-
+                 752.6    PERCENT BOUND IN SPECIES #9503300   ZnOH +
+                >1000.    PERCENT BOUND IN SPECIES #9503301   Zn(OH)2 AQ
+                >1000.    PERCENT BOUND IN SPECIES #9503302   Zn(OH)3 -
+                >1000.    PERCENT BOUND IN SPECIES #9503303   Zn(OH)4 -2
```

@

Zinc at pH 9.7 (pg 3)

```
+H2O
+                  1.5      PERCENT BOUND IN SPECIES #3300020   OH-

+                 64.2      PERCENT BOUND IN SPECIES #9503301   Zn(OH)2 AQ

+                 33.0      PERCENT BOUND IN SPECIES #9503302   Zn(OH)3 -

+                  1.2      PERCENT BOUND IN SPECIES #9503303   Zn(OH)4 -2



                 -------------------------------------------------------
                 ----------- EQUILIBRATED MASS DISTRIBUTION -----------
0
 IDX     NAME              DISSOLVED              SORBED              PRECIPITATED
                       MOL/KG    PERCENT     MOL/KG   PERCENT      MOL/KG    PERCENT

 950   Zn+2          3.073E-02   100.0    0.000E+00     0.0     0.000E+00     0.0
 180   Cl-1          6.178E-02   100.0    0.000E+00     0.0     0.000E+00     0.0
 500   Na+1          4.368E-03   100.0    0.000E+00     0.0     0.000E+00     0.0
 330   H+1          -3.967E-06   100.0    0.000E+00     0.0     0.000E+00     0.0
   2   H2O           7.065E-02   100.0    0.000E+00     0.0     0.000E+00     0.0
0
     CHARGE BALANCE: SPECIATED
0          SUM OF CATIONS =  7.504E-02 SUM OF ANIONS   7.100E-02
0          PERCENT DIFFERENCE =    2.767E+00   (ANIONS - CATIONS)/(ANIONS +
CATIONS)
0      NONCARBONATE ALKALINITY =    1.082E-03
0 IONIC STRENGTH = :  7.324E-02
1

   PC  VERSION: MINTEQA2   DATE OF CALCULATIONS: 08/24/89     TIME: 16:48:38

0Saturation indices and stoichiometry of all minerals
0    ID #     NAME      Sat. Index        Stoichiometry (in parentheses) of
each component
   4150000 HALITE          -5.356     (  1.000)500  (  1.000)180
   4195000 ZNCL2          -16.257     (  1.000)950  (  2.000)180
   2095000 ZN(OH)2 (A)      2.812     ( -2.000)330  (  1.000)950  (  2.000)  2
   2095001 ZN(OH)2 (C)      3.062     ( -2.000)330  (  1.000)950  (  2.000)  2
   2095002 ZN(OH)2 (B)      3.512     ( -2.000)330  (  1.000)950  (  2.000)  2
   2095003 ZN(OH)2 (G)      3.552     ( -2.000)330  (  1.000)950  (  2.000)  2
   2095004 ZN(OH)2 (E)      3.762     ( -2.000)330  (  1.000)950  (  2.000)  2
   4195001 ZN2(OH)3CL       3.080     ( -3.000)330  (  2.000)950  (  3.000)  2  (
1.000)180
   4195002 ZN5(OH)8CL2     13.322     ( -8.000)330  (  5.000)950  (  8.000)  2  (
2.000)180
   2095005 ZNO(ACTIVE)      3.953     ( -2.000)330  (  1.000)950  (  1.000)  2
   2095006 ZINCITE          4.123     ( -2.000)330  (  1.000)950  (  1.000)  2
```

APPENDIX D

ZINC/CADMIUM DATA

ZINC/CADMIUM ESD TEST

Test #	Distance Between Electrodes in.	Test Time Hr.	Voltage V/in.	Average Electrica Power watts	Average Acoustic Power watts	Acoustic Frequency HZ	Initial Cake weight gms	Final Cake weight gms	weight leachate collected gms	Final Solids Percent %	Final Cake PH	Initial Zinc Conc. mg/kg (DB)	Initial Cadmium Conc. mg/kg (DB)	Final Zinc Concentration Analytical Lab. Analysis: Zande Zinc Analysis mg/kg (DB)	Final Zinc Concentration Analytical Lab. Analysis: EPA Zinc Analysis mg/kg (DB)	Final Cadmium Concentration Analytical Lab. Analysis: Zande Cadmium Analysis mg/kg (DB)	Final Cadmium Concentration Analytical Lab. Analysis: EPA Cadmium Analysis mg/kg (DB	(x) Average Percent Zinc Removed	Average Percent Cadmium Removed	(b) Anode Flushing Solution PH	(c) Leachate PH	Comment
1 ZC-A	4.5	100	1.5 - 25.3	1.913	0	0	830	104.5	----	57.89	3.65	1093	920	107	150	29.2	25	85.09	97.06	3.98	7.2-7.8	cake incontact with Anode
1 ZC-B	4.5	100	1.5 - 25.3	1.913	0	0	830	173	----	60.93	3.55	1093	920	102	167	28	22	83.99	97.39	3.98	7.2-7.8	cake between layer A and C
1 ZC-C	4.5	100	1.5 - 25.3	1.913	0	0	830	175.0	----	64.85	3.64	1093	920	207	197	53.5	51	81.52	94.32	3.98	7.2-7.8	cake between layer B and B1
1 ZC-B1	4.5	100	1.5 - 25.3	1.913	0	0	830	119	----	65.16	4.12	1093	920	400	344	207	200	65.51	77.45	3.98	7.2-7.8	Cake between layer C and B2
1 ZC-B2	4.5	100	1.5 - 25.3	1.913	0	0	830	100.1	----	65.83	7--10	1093	920	7755	7150	6187	6310	----	----	3.98	7.2-7.8	cake incontact with Cathode

(b): PH of flushing water solution at the end of test

(c): PH of leachate at the end of test

(x): Percent Zinc Removed Based on Zande Analytical Data

APPENDIX E

GEOCHEMICAL CALCULATION FOR ZINC CADMIUM SOIL

Zinc and Cadmium at pH 7 (pg 1)

```
 PC  VERSION: MINTEQA2   DATE OF CALCULATIONS: 08/22/89     TIME: 13:12:44

      Zinc and Cadmium Solubility and Percent Distribution with Acetate at pH 7

--------------------------------------------------------------------------------
 Temperature (Celsius):  25.00
 Units of concentration: PPM
 Ionic strength to be computed.
 Carbonate concentration represents carbonate alkalinity.
 Do not automatically terminate if charge imbalance exceeds 30%
 Precipitation is allowed only for those solids specified as ALLOWED
   in the input file (if any).
 The maximum number of iterations is: 100
 The method used to compute activity coefficients is: Debye-Huckel equation
 Do not print the full species database including gram-formula weights and
   Debye-Huckel parameters.

--------------------------------------------------------------------------------
    950  0.100E+04   -1.82
    160  0.100E+04   -2.05
    180  0.200E+04   -1.25
    992  0.100E+04   -1.77
    500  0.385E+03   -1.78
    330  0.101E-04   -7.00
 H2O HAS BEEN INSERTED AS A COMPONENT
  3   1
    330     7.0000     0.0000
INPUT DATA BEFORE TYPE MODIFICATIONS
   ID        NAME          ACTIVITY GUESS    LOG GUESS   ANAL TOTAL
    950  Zn+2                   1.514E-02       -1.820   1.000E+03
    160  Cd+2                   8.913E-03       -2.050   1.000E+03
    180  Cl-1                   5.623E-02       -1.250   2.000E+03
    992  Acetate                1.698E-02       -1.770   1.000E+03
    500  Na+1                   1.660E-02       -1.780   3.850E+02
    330  H+1                    1.000E-07       -7.000   1.008E-05
      2  H2O                    1.000E+00        0.000   0.000E+00
   ID        NAME          ANAL MOL   CALC MOL   ACTIVITY   LOG ACTVTY      GAMMA
NEW LOGK     DIFF FXN
    950  Zn+2
0.0000    0.000E+00        1.000E+03  0.000E+00 1.514E-02   -1.82000     1.000000
    160  Cd+2
0.0000    0.000E+00        1.000E+03  0.000E+00 8.913E-03   -2.05000     1.000000
    180  Cl-1
0.0000    0.000E+00        2.000E+03  0.000E+00 5.623E-02   -1.25000     1.000000
    992  Acetate
0.0000    0.000E+00        1.000E+03  0.000E+00 1.698E-02   -1.77000     1.000000
    500  Na+1
0.0000    0.000E+00        3.850E+02  0.000E+00 1.660E-02   -1.78000     1.000000
```

Zinc and Cadmium at pH 7 (pg 2)

```
 9509921  ZN ACETATE     1.310E-03  0.0010387    -2.98352    0.792691      1.311
    0.000
 9509922  ZN ACETATE2    7.302E-05  0.0000743    -4.12899    1.017559      2.002
    0.000
 9509923  ZNACETATE3     4.430E-07  0.0000004    -6.45447    0.792691      1.731
    0.000

0    SPECIES:   TYPE  III - FIXED SOLIDS
0    ID        NAME        CALC MOL        LOG MOL      NEW LOGK       DH
       2  H2O             -1.796E-04       -3.746       0.001        0.000
     330  H+1              1.155E-04       -3.938       7.000        0.000
1

   PC  VERSION: MINTEQA2   DATE OF CALCULATIONS: 08/22/89     TIME: 13:13:18


  PERCENTAGE DISTRIBUTION OF COMPONENTS AMONG          dissolved and adsorbed
species


+Zn+2
+                85.0     PERCENT BOUND IN SPECIES #    950   Zn+2

+                 4.9     PERCENT BOUND IN SPECIES #9501800   ZnCl +

+                 8.5     PERCENT BOUND IN SPECIES #9509921   ZN ACETATE


+Cd+2
+                29.1     PERCENT BOUND IN SPECIES #    160   Cd+2

+                53.5     PERCENT BOUND IN SPECIES #1601800   CdCl +

+                 6.7     PERCENT BOUND IN SPECIES #1601801   CdCl2 AQ

+                 8.2     PERCENT BOUND IN SPECIES #1609921   CD ACETATE

+                 2.0     PERCENT BOUND IN SPECIES #1609922   CdACETATE2


+Cl-1
+                87.8     PERCENT BOUND IN SPECIES #    180   Cl-1

+                 1.3     PERCENT BOUND IN SPECIES #9501800   ZnCl +

+                 8.4     PERCENT BOUND IN SPECIES #1601800   CdCl +

+                 2.1     PERCENT BOUND IN SPECIES #1601801   CdCl2 AQ


+Acetate
+                84.0     PERCENT BOUND IN SPECIES #    992   Acetate
```

Zinc and Cadmium at pH 7 (pg 3)

```
   PC  VERSION: MINTEQA2   DATE OF CALCULATIONS: 08/22/89     TIME: 13:13:19

OSaturation indices and stoichiometry of all minerals
0     ID #      NAME       Sat. Index        Stoichiometry (in parentheses) of each
component
   4150000 HALITE          -4.868     (  1.000)500   (  1.000)180
   4195000 ZNCL2          -12.103     (  1.000)950   (  2.000)180
   2095000 ZN(OH)2 (A)     -0.700     ( -2.000)330   (  1.000)950   (  2.000)  2
   2095001 ZN(OH)2 (C)     -0.450     ( -2.000)330   (  1.000)950   (  2.000)  2
   2095002 ZN(OH)2 (B)      0.000     ( -2.000)330   (  1.000)950   (  2.000)  2
   2095003 ZN(OH)2 (G)      0.040     ( -2.000)330   (  1.000)950   (  2.000)  2
   2095004 ZN(OH)2 (E)      0.250     ( -2.000)330   (  1.000)950   (  2.000)  2
   4195001 ZN2(OH)3CL      -0.111     ( -3.000)330   (  2.000)950   (  3.000)  2  (
1.000)180
   4195002 ZN5(OH)8CL2      3.428     ( -8.000)330   (  5.000)950   (  8.000)  2  (
2.000)180
   2095005 ZNO(ACTIVE)      0.441     ( -2.000)330   (  1.000)950   (  1.000)  2
   2095006 ZINCITE          0.611     ( -2.000)330   (  1.000)950   (  1.000)  2
   4116000 CDCL2           -5.133     (  1.000)160   (  2.000)180
   4116001 CDCL2, 1H2O     -4.104     (  1.000)160   (  2.000)180   (  1.000)  2
   4116002 CDCL2,2.5H2O    -3.875     (  1.000)160   (  2.000)180   (  2.500)  2
   2016000 CD(OH)2 (A)     -2.720     ( -2.000)330   (  1.000)160   (  2.000)  2
   2016001 CD(OH)2 (C)     -2.640     ( -2.000)330   (  1.000)160   (  2.000)  2
   4116003 CDOHCL          -0.922     ( -1.000)330   (  1.000)160   (  1.000)  2  (
1.000)180
   2016002 MONTEPONITE     -4.109     ( -2.000)330   (  1.000)160   (  1.000)  2
```

Zinc and Cadmium at pH 8 (pg 1)

```
1

   PC  VERSION: MINTEQA2   DATE OF CALCULATIONS: 08/22/89     TIME:
11:43:35

     Zinc and Cadmium Solubility and Percent Distribution with Acetate at pH 8



--------------------------------------------------------------------------------
------
  Temperature (Celsius):  25.00
  Units of concentration: PPM
  Ionic strength to be computed.
  Carbonate concentration represents carbonate alkalinity.
  Do not automatically terminate if charge imbalance exceeds 30%
  Precipitation is allowed only for those solids specified as ALLOWED
    in the input file (if any).
  The maximum number of iterations is: 100
  The method used to compute activity coefficients is: Debye-Huckel
equation
  Do not print the full species database including gram-formula weights and
    Debye-Huckel parameters.


--------------------------------------------------------------------------------
-----
     950  0.100E+04   -1.82
     160  0.100E+04   -2.05
     180  0.200E+04   -1.25
     992  0.100E+04   -1.77
     500  0.385E+03   -1.78
     330  0.101E-04   -8.00
0 H2O HAS BEEN INSERTED AS A COMPONENT
   3   1
     330     8.0000      0.0000
0INPUT DATA BEFORE TYPE MODIFICATIONS
0    ID          NAME         ACTIVITY GUESS    LOG GUESS   ANAL TOTAL
     950  Zn+2                     1.514E-02       -1.820   1.000E+03
     160  Cd+2                     8.913E-03       -2.050   1.000E+03
     180  Cl-1                     5.623E-02       -1.250   2.000E+03
     992  Acetate                  1.698E-02       -1.770   1.000E+03
     500  Na+1                     1.660E-02       -1.780   3.850E+02
     330  H+1                      1.000E-08       -8.000   1.008E-05
       2  H2O                      1.000E+00        0.000   0.000E+00
0    ID          NAME         ANAL MOL   CALC MOL   ACTIVITY    LOG ACTVTY
GAMMA      NEW LOGK     DIFF FXN
     950  Zn+2               1.000E+03  0.000E+00 1.514E-02     -1.82000
1.000000       0.0000    0.000E+00
     160  Cd+2               1.000E+03  0.000E+00 8.913E-03     -2.05000
1.000000       0.0000    0.000E+00
```

Zinc and Cadmium at pH 8 (pg 2)

```
 1609922  CdACETATE2      1.877E-04  0.0001909     -3.71925     1.016802
3.143      0.000
 1609923  CdACETATE3      2.895E-07  0.0000002     -6.63772     0.795396
2.269      0.000
 1609924  CdACETATE4      4.914E-09  0.0000000     -8.70620     0.400251
2.438      0.000
 9509921  ZN ACETATE      1.182E-03  0.0009403     -3.02674     0.795396
1.309      0.000
 9509922  ZN ACETATE2     6.723E-05  0.0000684     -4.16522     1.016802
2.003      0.000
 9509923  ZNACETATE3      4.128E-07  0.0000003     -6.48369     0.795396
1.729      0.000

0    SPECIES:   TYPE  III - FIXED SOLIDS
0   ID          NAME         CALC MOL         LOG MOL       NEW LOGK       DH
       2  H2O              -2.730E-03        -2.564        0.001        0.000
     330  H+1               2.724E-03        -2.565        8.000        0.000
1

   PC  VERSION: MINTEQA2   DATE OF CALCULATIONS: 08/22/89     TIME:
11:44:08


  PERCENTAGE DISTRIBUTION OF COMPONENTS AMONG          dissolved and
adsorbed species


+Zn+2
+                   74.8     PERCENT BOUND IN SPECIES #     950    Zn+2

+                    4.3     PERCENT BOUND IN SPECIES #9501800    ZnCl +

+                    4.5     PERCENT BOUND IN SPECIES #9503300    ZnOH +

+                    4.0     PERCENT BOUND IN SPECIES #9503301    Zn(OH)2 AQ

+                    4.1     PERCENT BOUND IN SPECIES #9501804    ZnOHCl AQ

+                    7.7     PERCENT BOUND IN SPECIES #9509921    ZN ACETATE

+Cd+2
+                   28.4     PERCENT BOUND IN SPECIES #     160    Cd+2

+                   52.6     PERCENT BOUND IN SPECIES #1601800    CdCl +

+                    6.6     PERCENT BOUND IN SPECIES #1601801    CdCl2 AQ

+                    1.7     PERCENT BOUND IN SPECIES #1601803    CdOHCl AQ

+                    8.3     PERCENT BOUND IN SPECIES #1609921    CD ACETATE

+                    2.1     PERCENT BOUND IN SPECIES #1609922    CdACETATE2
```

Zinc and Cadmium at pH 8 (pg 3)

```
0
     CHARGE BALANCE: SPECIATED
0           SUM OF CATIONS =  5.282E-02 SUM OF ANIONS   6.380E-02
0           PERCENT DIFFERENCE =   9.417E+00   (ANIONS - CATIONS)/(ANIONS +
CATIONS)
0      NONCARBONATE ALKALINITY =   1.277E-06
0 IONIC STRENGTH = :  7.236E-02
1    .

   PC  VERSION: MINTEQA2   DATE OF CALCULATIONS: 08/22/89     TIME: 11:44:09

0Saturation indices and stoichiometry of all minerals
0     ID #      NAME       Sat. Index        Stoichiometry (in parentheses) of each
component
   4150000 HALITE          -4.869     (  1.000)500   (   1.000)180
   4195000 ZNCL2          -12.158     (  1.000)950   (   2.000)180
   2095000 ZN(OH)2 (A)      1.250     ( -2.000)330   (   1.000)950   (   2.000)  2
   2095001 ZN(OH)2 (C)      1.500     ( -2.000)330   (   1.000)950   (   2.000)  2
   2095002 ZN(OH)2 (B)      1.950     ( -2.000)330   (   1.000)950   (   2.000)  2
   2095003 ZN(OH)2 (G)      1.990     ( -2.000)330   (   1.000)950   (   2.000)  2
   2095004 ZN(OH)2 (E)      2.200     ( -2.000)330   (   1.000)950   (   2.000)  2
   4195001 ZN2(OH)3CL       2.786     ( -3.000)330   (   2.000)950   (   3.000)  2  (
1.000)180
   4195002 ZN5(OH)8CL2     11.172     ( -8.000)330   (   5.000)950   (   8.000)  2  (
2.000)180
   2095005 ZNO(ACTIVE)      2.391     ( -2.000)330   (   1.000)950   (   1.000)  2
   2095006 ZINCITE          2.561     ( -2.000)330   (   1.000)950   (   1.000)  2
   4116000 CDCL2           -5.142     (  1.000)160   (   2.000)180
   4116001 CDCL2, 1H2O     -4.113     (  1.000)160   (   2.000)180   (   1.000)  2
   4116002 CDCL2,2.5H2O    -3.884     (  1.000)160   (   2.000)180   (   2.500)  2
   2016000 CD(OH)2 (A)     -0.724     ( -2.000)330   (   1.000)160   (   2.000)  2
   2016001 CD(OH)2 (C)     -0.644     ( -2.000)330   (   1.000)160   (   2.000)  2
   4116003 CDOHCL           0.072     ( -1.000)330   (   1.000)160   (   1.000)  2  (
1.000)180
   2016002 MONTEPONITE     -2.113     ( -2.000)330   (   1.000)160   (   1.000)  2
```

Zinc and Cadmium at pH 9 (pg 1)

```
1
   PC  VERSION: MINTEQA2   DATE OF CALCULATIONS: 08/22/89      TIME: 13:10:06

          Zinc and Cadmium Solubility and Percent Distribution with Acetate at pH 9

-------------------------------------------------------------------------------
  Temperature (Celsius):  25.00  .
  Units of concentration: PPM
  Ionic strength to be computed.
  Carbonate concentration represents carbonate alkalinity.
  Do not automatically terminate if charge imbalance exceeds 30%
  Precipitation is allowed only for those solids specified as ALLOWED
    in the input file (if any).
  The maximum number of iterations is: 100
  The method used to compute activity coefficients is: Debye-Huckel equation
  Do not print the full species database including gram-formula weights and
    Debye-Huckel parameters.

-------------------------------------------------------------------------------
     950  0.100E+04   -1.82
     160  0.100E+04   -2.05
     180  0.200E+04   -1.25
     992  0.100E+04   -1.77
     500  0.385E+03   -1.78
     330  0.101E-04   -9.00
0 H2O HAS BEEN INSERTED AS A COMPONENT
   3   1
     330      9.0000      0.0000
0INPUT DATA BEFORE TYPE MODIFICATIONS
0    ID          NAME         ACTIVITY GUESS     LOG GUESS    ANAL TOTAL
     950   Zn+2                    1.514E-02        -1.820    1.000E+03
     160   Cd+2                    8.913E-03        -2.050    1.000E+03
     180   Cl-1                    5.623E-02        -1.250    2.000E+03
     992   Acetate                 1.698E-02        -1.770    1.000E+03
     500   Na+1                    1.660E-02        -1.780    3.850E+02
     330   H+1                     1.000E-09        -9.000    1.008E-05
       2   H2O                     1.000E+00         0.000    0.000E+00
0    ID          NAME         ANAL MOL    CALC MOL    ACTIVITY    LOG ACTVTY      GAMMA
  NEW LOGK     DIFF FXN
     950   Zn+2              1.000E+03   0.000E+00 1.514E-02     -1.82000     1.000000
  0.0000     0.000E+00
     160   Cd+2              1.000E+03   0.000E+00 8.913E-03     -2.05000     1.000000
  0.0000     0.000E+00
     180   Cl-1              2.000E+03   0.000E+00 5.623E-02     -1.25000     1.000000
  0.0000     0.000E+00
     992   Acetate           1.000E+03   0.000E+00 1.698E-02     -1.77000     1.000000
  0.0000     0.000E+00
     500   Na+1              3.850E+02   0.000E+00 1.660E-02     -1.78000     1.000000
  0.0000     0.000E+00
```

Zinc and Cadmium at pH 9 (pg 2)

```
 9509921  ZN ACETATE     2.208E-04  0.0001803    -3.74407     0.816306      1.298
    0.000
 9509922  ZN ACETATE2    1.429E-05  0.0000145    -4.83980     1.011920      2.005
    0.000
 9509923  ZNACETATE3     9.389E-08  0.0000001    -7.11553     0.816306      1.718
    0.000

0     SPECIES:    TYPE  III - FIXED SOLIDS
0    ID          NAME           CALC MOL         LOG MOL       NEW LOGK       DH
        2  H2O              -2.561E-02        -1.592        0.001        0.000
      330  H+1               2.561E-02        -1.592        9.000        0.000
1

   PC  VERSION: MINTEQA2   DATE OF CALCULATIONS: 08/22/89     TIME: 13:10:39


  PERCENTAGE DISTRIBUTION OF COMPONENTS AMONG          dissolved and adsorbed
species


+Zn+2
+                 11.9     PERCENT BOUND IN SPECIES #     950    Zn+2

+                  7.6     PERCENT BOUND IN SPECIES #9503300    ZnOH +

+                 70.6     PERCENT BOUND IN SPECIES #9503301    Zn(OH)2 AQ

+                  7.3     PERCENT BOUND IN SPECIES #9501804    ZnOHCl AQ

+                  1.4     PERCENT BOUND IN SPECIES #9509921    ZN ACETATE


+Cd+2
+                 22.2     PERCENT BOUND IN SPECIES #     160    Cd+2

+                 45.5     PERCENT BOUND IN SPECIES #1601800    CdCl +

+                  6.0     PERCENT BOUND IN SPECIES #1601801    CdCl2 AQ

+                  1.0     PERCENT BOUND IN SPECIES #1603300    CdOH +

+                 15.1     PERCENT BOUND IN SPECIES #1601803    CdOHCl AQ

+                  7.7     PERCENT BOUND IN SPECIES #1609921    CD ACETATE

+                  2.2     PERCENT BOUND IN SPECIES #1609922    CdACETATE2


+Cl-1
+                 86.3     PERCENT BOUND IN SPECIES #     180    Cl-1

+                  2.0     PERCENT BOUND IN SPECIES #9501804    ZnOHCl AQ
```

Zinc and Cadmium at pH 9 (pg 3)

```
   2  H2O            2.561E-02   100.0   0.000E+00     0.0   0.000E+00      0.0
 330  H+1           -2.561E-02   100.0   0.000E+00     0.0   0.000E+00      0.0
0
     CHARGE BALANCE: SPECIATED
0           SUM OF CATIONS =  3.071E-02 SUM OF ANIONS   6.457E-02
0           PERCENT DIFFERENCE =   3.554E+01   (ANIONS - CATIONS)/(ANIONS +
CATIONS)
0   '  NONCARBONATE ALKALINITY =   1.239E-05
0 IONIC STRENGTH = :  5.146E-02
1

   PC  VERSION: MINTEQA2   DATE OF CALCULATIONS: 08/22/89     TIME: 13:10:40

0Saturation indices and stoichiometry of all minerals
0     ID #      NAME        Sat. Index         Stoichiometry (in parentheses) of each
component
    4150000 HALITE             -4.848     (  1.000)500  (  1.000)180
    4195000 ZNCL2             -12.897     (  1.000)950  (  2.000)180
    2095000 ZN(OH)2 (A)         2.490     ( -2.000)330  (  1.000)950  (  2.000)  2
    2095001 ZN(OH)2 (C)         2.740     ( -2.000)330  (  1.000)950  (  2.000)  2
    2095002 ZN(OH)2 (B)         3.190     ( -2.000)330  (  1.000)950  (  2.000)  2
    2095003 ZN(OH)2 (G)         3.230     ( -2.000)330  (  1.000)950  (  2.000)  2
    2095004 ZN(OH)2 (E)         3.440     ( -2.000)330  (  1.000)950  (  2.000)  2
    4195001 ZN2(OH)3CL          4.276     ( -3.000)330  (  2.000)950  (  3.000)  2  (
1.000)180
    4195002 ZN5(OH)8CL2        15.393     ( -8.000)330  (  5.000)950  (  8.000)  2  (
2.000)180
    2095005 ZNO(ACTIVE)         3.631     ( -2.000)330  (  1.000)950  (  1.000)  2
    2095006 ZINCITE             3.801     ( -2.000)330  (  1.000)950  (  1.000)  2
    4116000 CDCL2              -5.183     (  1.000)160  (  2.000)180
    4116001 CDCL2, 1H2O        -4.154     (  1.000)160  (  2.000)180  (  1.000)  2
    4116002 CDCL2,2.5H2O       -3.925     (  1.000)160  (  2.000)180  (  2.500)  2
    2016000 CD(OH)2 (A)         1.214     ( -2.000)330  (  1.000)160  (  2.000)  2
    2016001 CD(OH)2 (C)         1.294     ( -2.000)330  (  1.000)160  (  2.000)  2
    4116003 CDOHCL              1.020     ( -1.000)330  (  1.000)160  (  1.000)  2  (
1.000)180
    2016002 MONTEPONITE        -0.175     ( -2.000)330  (  1.000)160  (  1.000)  2
```